Thesis for the degree of Licentiate of Engineering

Aerodynamics of two trucks driving in close-proximity

JOHANNES TÖRNELL

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2021

Aerodynamics of two trucks driving in close-proximity
JOHANNES TÖRNELL

THESIS FOR LICENTIATE OF ENGINEERING no 2021:15

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE–412 96 Göteborg
Sweden
Telephone: +46 (0)31–772 1000

Cover:
Iso-surfaces of the instantaneous q-criterion colored by velocity for two trucks in close proximity.

Chalmers Reproservice
Göteborg, Sweden 2021

""What is the airspeed velocity of an unladen swallow?" -Bridgekeeper"

Aerodynamics of two trucks driving in close-proximity

Johannes Törnell
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

There are several factors driving the development of vehicles with higher efficiency in society, chief among them are the emissions of greenhouse gases and their contribution to global warming. Therefore, there is a strong incentive to improve heavy-duty trucks' energy efficiency, supported by new legislation. This focus, combined with growing demands for transport, drives vehicle manufacturers to improve their vehicles. One of the important ways to increase the energy efficiency of vehicles is to reduce their aerodynamic resistance. There are, however, limitations on how much the aerodynamics of a vehicle can be refined. As the development of current technologies nears this limit, it becomes more expensive and difficult to further reduce drag. It is, therefore, fundamental to identify new ways to decrease the aerodynamic drag of vehicles. This, in conjunction with improvements in vehicle automation and sensor technology, has spurred a renewed interest in vehicles driving in close proximity to each other, also known as platooning.

Although there is interest in this topic, a lack of understanding remains concerning the phenomena that cause changes in drag when two or more vehicles are traveling in a platoon. Furthermore, the behavior of platooning cab over engine style trucks that are common in the European Union is not well understood. The focus of this work lies in understanding such a system's behavior and producing data that shows the changes in drag observed for two cab over engine style trucks driving in close proximity.

The work was split into two different studies: the initial part was based on numerical results, and the second on experimental ones obtained in the Volvo Cars wind tunnel. The results show that the behavior of the leading truck is simple, where a closer inter-vehicle distance will mean a lower drag. The trailing truck has a more complex behavior, where there are both local minima and maxima with respect to the drag experienced as the separation distance between the vehicles is reduced. The effects that cause the changes in drag are many but can be generally defined as the leading truck mainly being affected by differences in pressure, and the trailing truck affected mainly by changes in the flow due to the wake of the leading vehicle. The combined changes in drag of the two vehicles result in a continuous decrease in drag with a reduced inter-vehicle distance.

Keywords: aerodynamics, drag, wake, side wind, platooning, close proximity, lateral offset, inter-vehicle distance, yaw, cab over engine, truck

Acknowledgements

The work presented here would not have been possible were it not for the multitude of people who have lent me their support throughout. First, I would like to thank my main supervisor Prof. Simone Sebben for all her support and feedback, especially with regard to the writing process during times of struggle. I would also like to thank all of my current and past industrial supervisors, all of whom have shown a great interest in the project and provided valuable insight into different areas. Dr. Per Elofsson for all his invaluable knowledge on truck aerodynamics and for supporting me in the experimental campaigns, both in the planning and execution. Dr. David Söderblom for all of his support in the early parts of the project, for helping me learn about the aerodynamics of trucks and for all the discussions on how to develop the numerical method. Alexander Broniewicz for all the help from the side of Volvo Cars and for helping me bring the right people together to enable the experimental campaign to move forward. Vojtech Sedlak for all of his help in navigating the channels at Volvo Cars, and for the many great discussions. Further, I would like to extend my thanks to all of the people at both Volvo Cars and at Scania for their help in preparing for and executing my slightly unorthodox wind tunnel experiments.

I would also like to thank the Swedish Energy Agency, Scania, and Volvo Cars for their funding of this project, without which none of this would have been possible. Next, I would like to thank the Swedish National Infrastructure for Supercomputing (SNIC), Chalmers Center for Computational Science (C3SE), and the National Supercomputer Centre (NSC) for their support with computing resources, which has enabled much of this work.

I express my gratitude toward my colleagues, past and present, and friends at VEAS for all of their support and for cultivating an amazing work environment. For all of the great exchanges that have been had, both on- and off-topic, and for all of the fun activities, thank you. I would also like to thank Sonja for always being supportive and bringing the group together, even in these challenging times.

To my family, thank you for always supporting me, believing in me, and inspiring me to keep forging my own path. To my friends outside of Chalmers, thank you for all of your support, for all the great times, and for keeping me in check and distracting me from work when I have needed it. Finally, to my dearest Christina, thank you for your love, all of your support both in helping me proofread and in life with giving me endless laughs and distracting me when I need it the most. For this, I am eternally grateful.

Nomenclature

A	Area	$[m^2]$
C_D	Drag coefficient	[-]
$C_\mathrm{D}A$	Drag area	$[m^2]$
$C_\mathrm{D\ counts}$	Drag coefficient in counts, $1C_\mathrm{D\ count} = 0.001\ C_\mathrm{D}$	[-]
C_P	Pressure coefficient	[-]
C_r	Rolling resistance coefficient	[-]
m	Mass	[kg]
u_i	Velocity component i	[m/s]
f	Frequency	[Hz]
Re	Reynolds Number	[-]
Σ	Standard Deviation	[-]
Σ_i	Standard deviation of drag with i averaged samples	[-]
n	number of samples	[-]
k	number of samples available	[-]
i	number of samples used for averaging	[-]
ΔF_avg	uncertainty of force measurement	[-]
k_res	resolved turbulent kinetic energy	[J]
k_mod	modeled turbulent kinetic energy	[J]
$u'_\mathrm{i\ X1}$	Velocity component i fluctuation for point X1	[m/s]
$u'_\mathrm{i\ X2}$	Velocity component i fluctuation for point X2	[m/s]
$u_\mathrm{i\ RMS\ X1}$	Root mean square of the velocity component i fluctuation for point X1	[m/s]

Abbreviations

CFD	Computational Fluid Dynamics
CFL	Courant-Freidrichs-Lewy
CO_2	Carbon Dioxide
COE	Cab-over Engine
EU	European Union
GHG	Greenhouse Gas
IDDES	Improved Delayed Detached Eddy Simulation
IVD	Inter-Vehicle Distance
LES	Large Eddy Simulation
OEM	Original Equipment Manufacturer
RANS	Reynolds Averaged Navier Stokes
SUV	Sports Utility Vehicle
SST	Shear-Stress Transport
TVR	Turbulent Viscosity Ratio
URANS	Unsteady Reynolds Averaged Navier Stokes

Thesis

This thesis consists of an extended summary of the two included papers, listed below.

I. Törnell J., Sebben S. and Söderblom D., *Influence of inter-vehicle distance on the aerodynamics of a two-truck platoon*in: International Journal of Automotive Technology, Vol. 22, No. 3, pp. 747–760 (2021), DOI 10.1007/s12239–021–0068–5

II. Törnell J., Sebben S. and Elofsson P., *Experimental investigation of a two-truck platoon considering inter-vehicle distance, lateral offset and yaw* in: Journal of Wind Engineering and Industrial Aerodynamics, Volume 213, 2021, 104596, ISSN 0167-6105, https://doi.org/10.1016/j.jweia.2021.104596.

Division of work

I. All setup, simulation work and formal analysis for Paper I was done by Törnell. Törnell wrote the first manuscript which was discussed, reviewed and revised by all authors.

II. The instrumentation of the models was done by Törnell. The original plan for the experiments was done by Törnell and then discussed and revised by all authors. The experiments were performed by Törnell and Elofsson. The formal analysis of the results was done by Törnell. Törnell wrote the first manuscript which was discussed, reviewed and revised by all authors.

Table of Contents

Part I

Extended summary

Chapter 1

Introduction

As the society we live in moves toward a more connected and delivery-based way of life, seen by the rise of online purchasing of goods, the use of road transport has intensified. For this lifestyle to be a sustainable way forward, the emissions and energy usage of road transport must be reduced. Today, roughly 28% of the greenhouse gas (GHG) emissions from transport in Europe come from light- and heavy-duty trucking [1]. Although this number is significantly smaller than that for passenger cars (roughly 45%), truck manufacturers and operating truck companies are pressured to reduce their carbon footprint. This is due to strict governmental regulations, people's awareness of the harmful effects of GHG emissions on the global climate, and the fact that for the operating truck businesses, fuel consumption represents roughly one third of the total cost of ownership. A transition to electrification in both the private and commercial transport sectors has been initiated. Notably, the electrification of long-distance trucking is more problematic than that of passenger cars, as the energy consumption of long-distance trucking is much larger per vehicle and, therefore, will take longer.

One way to lower greenhouse gas emissions and decrease energy usage of vehicles is to reduce their aerodynamic resistance. There are several ways to accomplish better aerodynamics, and all Original Equipment Manufacturers (OEM) work continuously toward delivering products with lower drag values. There is, however, a limit on how low drag values can be achieved for individual vehicles using established aerodynamic solutions, and companies are finding it more difficult to find further improvements. As an alternative to reduce the fleet average energy consumption, concepts such as platooning (two or more vehicles driving in close proximity) are being considered. Although platooning has long been envisioned as a way to reduce the aerodynamic resistance in road transport, it is only recently that the concept has become more realistic as sensor and vehicle automation technology progresses, allowing vehicles to travel safely in close proximity.

Despite the large body of literature available on the aerodynamic gains and the flow around simplified vehicle bodies traveling in a convoy, there is a knowledge gap regarding this type of flow around more complex geometries. Therefore, this thesis aims to complement and increase the understanding of the aerodynamic behavior of realistic vehicle shapes in close proximity. The initial focus of the work is on the development of experimental and numerical procedures for measuring, calculating, and analyzing the flow phenomena using two detailed cab over engine style trucks, common in Europe.

1.1 Objectives

This thesis is a part of a Ph.D. project at Chalmers University of Technology in collaboration with Scania CV and Volvo Car Corporation. The main objective of this project is to better understand the behavior of vehicles traveling in a platoon and how to maximize their performance. The project can be split into several sub-objectives:

- Map and understand the behavior of aerodynamic resistance of different vehicles at varying inter-vehicle distances, lateral offsets, and yaw angles
- Understand the flow physics and phenomena that create the changes mapped in the first objective.
- Understand how these phenomena can be used or negated to improve the performance in different scenarios.
- Test these hypotheses numerically and experimentally to investigate their effect on the performance.

The investigations in this project will be carried out using both numerical and experimental tools to enable both a thorough understanding of the system and to validate the results.

1.2 Limitations

- Numerical and experimental resources are limited in this project; this means that not all combinations will be investigated.
- Wind tunnel size and time are limited. As such, many configurations cannot be investigated using experimental methods and thus have to be investigated numerically.
- Only one design of each vehicle type (truck, bus, SUV) will be used in this project, as creating more physical models is outside the project's budget.
- Due to time and budget constraints, only limited modifications will be done to the vehicles to optimize their performance in a platoon.

1.3 Outline

The following section will be a review of previous literature on the subject of platooning. After that, a section on the methods used, both numerical and experimental, will be presented. Thereafter the results from the two studies will be presented and discussed. The thesis will then end with conclusions, future work, and the appended papers.

Chapter 2

Background

2.1 Environmental aspects

As global warming and pollution issues are becoming more evident and prevalent, legislation is drafted and passed to combat further degradation. Roughly 12% of global greenhouse gas emissions are emitted by road transport, of which 40% is freight [2]. Some research has found that the potential reduction in fuel consumption from platooning is up to 15% [3–7] which would yield a total reduction of 360 million tons of CO_2 per year or 0.7% of the annual global emissions. This, however, is likely the upper limit. Realistic reductions should be significantly lower as the conditions for platooning are not always optimal. A large reduction is still expected with the implementation of platooning and is thus an alternative of interest. Furthermore, new European legislation has been adopted, forcing truck manufacturers to reduce their average fleet CO_2 emissions 15% by 2025 and 30% by 2030, further pressuring OEMs to find new solutions.

2.2 Aerodynamics of trucks

As discussed in the introduction, there is a considerable drive to reduce the fuel consumption of road vehicles with multiple contributing factors, especially for trucks. There are numerous ways to reduce the fuel consumption of vehicles and, in the case of electric vehicles, energy consumption. The focus in this thesis lies in the reduction of the forces acting to decelerate the vehicle, in particular the aerodynamic forces. The aerodynamic forces become dominant at roughly 80 km/h, although this is highly dependent on vehicle weight, making them important to reduce for highway transport (Figure 2.1).

There are various methods to reduce the aerodynamic drag of a truck, some of which are easier to implement than others. Some of these are not feasible to use, at least in the EU, where the maximum length of the complete vehicle is restricted, e.g., boat tail and front end extensions. Other possibilities are available such as optimizing the shape of the cab and underbody as well as air-deflectors on the cab, which has been a feature on trucks for a long time. This air-deflector has to be set correctly as the aerodynamic drag is sensitive to the angle of the deflector, as shown by Cooper [8]. Furthermore, some modifications can be made to the trailer, such as

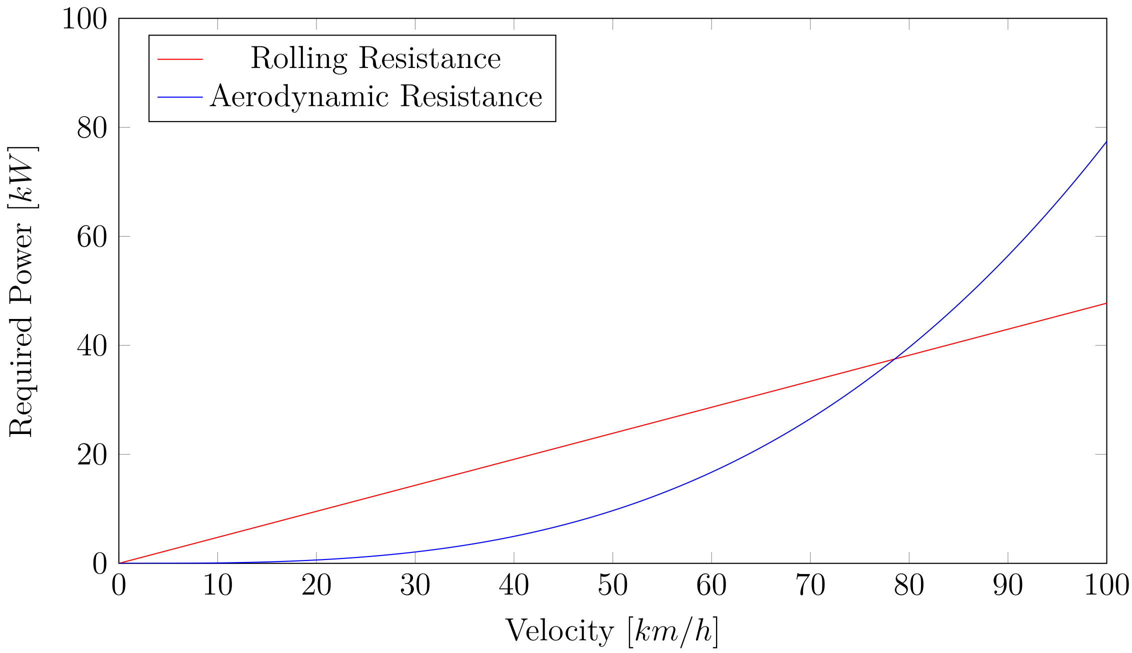


Figure 2.1: *Power required to overcome rolling and aerodynamic resistances. Cd=0.6, A=10m^2, Cr=0.005, m=35000kg*

adding skirts to the underbody. There are, however, issues with these that limits their adaptation on the road. All of these features or additions have limitations, and as vehicles become increasingly aerodynamic and the existing features become more refined, new methods have to be found and adopted. Many of these have been studied and consistently show that they will reduce the aerodynamic drag efficiently [8–12]. Another commonly used feature to reduce the drag of a truck is front edge rounding, which is quite sensitive with respect to Reynolds number and yaw according to Cooper [13].

The large size of trucks gives rise to difficulties in experimental investigations, which means that aerodynamic analysis of trucks using scale models is commonplace. This downsizing of the model presents several issues that have to be addressed, such as their Reynolds behavior, which can be effected by yaw [14], for example. Studies have recommended that Reynolds numbers in excess of 3 million based on the square root of the frontal area should be used [15]. Leuschen suggests that if a Reynolds number equivalent to less than 40% of full scale is used, several speed sweeps should be performed to ensure Reynolds independence of the results [14]. Moving ground simulation also has the potential to affect the results where the influence of air-deflectors can be sensitive to the use of a moving ground system [16]. Comparisons have been made between scale models and full-scale trucks which have shown good correlation for smaller yaw angles. The discrepancy at large yaw angles is partially thought to be due to blockage effects that are difficult to compensate for [17]. Another way of investigating the aerodynamics of trucks is through numerical simulations, which have been shown to yield good results by Martini et al. [18], especially when unsteady approaches are used as shown by Sengupta et al. [19].

2.3 Platooning

Vehicles driving in close proximity, or platooning, has long been envisioned as a means to reduce the fuel consumption of road vehicles. McAuliffe et al. and Mihelic et al. have shown that the efficiency of a double trailer configuration is more efficient than two trucks in a close proximity [20, 21]. This, however, does not negate the possible benefits. This is the case as double trailers might not yield sufficient cargo capacity or be the desired solution. The formation of platoons has been investigated in several studies and has shown that small adjustments to departure schedules have the potential to increase the number of platoons on the road [22, 23]. Although many obstacles for real-world platooning remain, such as vehicle communication, legislation, planning, and safety, further research is needed to understand the potential benefits and drawbacks. Moreover, the benefits of driving in close proximity are not limited to the aerodynamic improvements but stretch further into optimal control and potentially several automated vehicles led by a single truck with a driver.

2.4 Literature review

As the concept of platooning is not a new one, there is a significant body of literature on the subject. This, however, is focused on either very simple bodies or North American style trucks. This section is split up into four parts: three based on the different ways of analyzing the performance of vehicles in close proximity and one section on studies in other areas that are applicable to platooning.

2.4.1 Fuel consumption testing

The main benefits of using fuel consumption testing on a test track to analyze platooning are that the real change in fuel consumption can be observed as well as it being the closest possible way of testing to a real-world case. However, this method has several drawbacks, such as limited data into the actual aerodynamics and difficulty in separating out the change in aerodynamic drag. Further, it is also challenging to compensate for all environmental factors such as temperature, wind, and atmospheric pressure. As will be discussed in this thesis, the influence of yaw conditions can be significant on the performance seen in a platooning scenario. There have numerous such studies performed, both using North American style trucks as well as cab over engine (COE) style trucks. Several studies on the effects of inter-vehicle distance have been done and show savings of up to 8% for the leading truck and 20% for the trailing truck [3–7, 24, 25]. Arturo et al. also included cars where the maximum saving for a trailing car was 16% [3]. However, some effects can reduce the efficiency of platooning such as engine fans being utilized to cool the engine [26], lateral offset [27], curved roads [27], and cut ins from surrounding traffic [28], some of which can be potentially mitigated by different solutions. The magnitude of the penalty varies between the different studies. Furthermore, several changes can be made to further increase the efficiency of vehicles driving in close proximity, such as improving the aerodynamics of the trailer and the effects from surrounding traffic which both have been reported to be mostly additive by Bonnet et al. and McAuliffe et al. [5, 29]. In the case of using different variations of trailers, it can be important to position the vehicles correctly as different trailers will yield different savings depending on their position, as shown by McAuliffe et al. [28]. Finally, the drag trends for the leading and trailing truck differ greatly. It has been shown that the leading truck only sees a benefit of driving in front of another vehicle for relatively short inter-vehicle distances (IVDs) whereas the trailing truck sees a significant benefit even at longer distances [20, 30, 31] and exhibits a local minima of savings at shorter distances [5, 20, 32, 33].

2.4.2 Wind tunnel experiments

To avoid some of the downsides of fuel consumption testing, it is also possible to investigate these phenomena in a wind tunnel. This has the benefit of a stable test environment and accurate measurements of aerodynamic forces. However, it has a similar drawbacks to those of the fuel consumption testing, where it is often difficult, slow, or expensive to measure the flow around the vehicles. Further, it is often complicated to create a realistic scenario, due to the need for fairly small-scale models as well as difficulties in using a rolling road. As these limitations can be challenging to overcome regarding available wind tunnels and costs, many currently published studies have utilized small scale-models with stationary ground planes. Several different styles of trucks and cars have been used in investigations of close proximity driving in wind tunnels or similar facilities and have given a good insight into the general behavior of platoons.

It has been shown in many studies that the aerodynamic shape of the vehicles driven in close proximity is of great importance and generally favors less aerodynamic vehicles. Particularly favorable are non-aerodynamic bases on the vehicles leading others and a non-aerodynamic front for vehicles trailing others [34–44]. The effects of platooning have also been shown to be the strongest toward the nearest neighbors in the platoon, where changes in IVD to the vehicle immediately in front or behind have the overwhelmingly largest impact [45, 46]. Wind tunnel tests show similar trends to the fuel economy tests done on road in terms of a local minima in the aerodynamic drag reduction [36, 40, 43, 47–50], reduced cooling [47], effects from surrounding traffic [38] and some negative impact from lateral offset with no side wind [49]. As the conditions are more controllable in a wind tunnel, there are effects that could not be analyzed on road that have been in the wind tunnel. Some of these are the effects of yaw, where some reduction in efficiency to driving in close proximity has been seen. With regards to yaw, this effect, however, has been shown to be small at short IVDs by Marcu et al. [51]. McAuliffe et al. have shown that improvements can be made using lateral offset in yaw conditions [47]. Moreover, longer platoons have also been investigated experimentally and have shown larger savings with more vehicles [48] as well as a plateau in the drag of the mid to late vehicles in a platoon [34, 44, 52], indicating that these numbers could be extended to represent a significantly longer convoy. It has been noted that some of the effects of vehicles driving in close proximity show similar trends to the behavior of a tractor-trailer gap when changing the gap length [42]. Finally, Telionis et al. attempted to identify the flow phenomena that affect vehicles in close proximity [50], and Tadakuma et al. tried to develop a mathematical model to estimate the drag of vehicles driving in close proximity [53].

2.4.3 Numerical investigations

To further analyze the system and gain more insight into the flow, numerical simulations can be used. They can also be a significantly cheaper option. The downside to numerical simulations is the uncertainty of the accuracy toward the real world. Further, numerical simulations can be significantly more expensive when, for example, investigating the general behavior of vehicles driving in close proximity, which would require a large number of simulations. Many different approaches to simulations have been taken in other studies, where most have used either simplified geometry or numerical models. It has been seen in unpublished results by the author that some simpler numerical models can give erroneous results. The poor suitability of RANS for long IVDs has also been demonstrated by Humphreys et al.[54], and hybrid RANS/LES models have been recommended [15].

The drag reduction trends seen in numerical studies generally agree with experimental studies, such as small to no effect on the leading vehicle when the IVD is greater than 20m shown by Smith et al. [55] and fuel savings of up to 23% [56]. It has also been shown that the effects of lateral offset can be detrimental to the performance when driving in close proximity [54, 57, 58], with the trailing truck being more affected than the leading truck [54]. Driving side by side has been shown by Vegendla et al. to have a significant negative impact on aerodynamic drag [56]. The large effect on the trailing vehicle from yaw [55] has, as in experimental studies, been partially mitigated by the use of lateral offset [59]. Similar effects to those seen in wind tunnel studies where longer platoons yielded larger savings and a plateau of drag toward the end, have also been seen in numerical studies [60].

Numerical studies have largely been used to understand the phenomena affecting vehicles in close proximity. Bruneau et al. have shown that the effects on the leading vehicle are predominately pressure-based and stem from the stagnation pressure of the trailing truck [61]. The same study also showed that the effects on the trailing vehicle originate from changes to the flow due to the wake of the leading vehicle [61]. The flow phenomena affecting cars in close proximity have also been explained by Ebrahim et al. [62]. It has been shown in some studies that the drag for the trailing truck does not strictly decrease with distance [59, 62, 63]. A potential explanation for this was presented by Gheyssens et al. as the sensitive nature of frontal edge rounding [64]. Another reason for this behavior has been put forth by Ebrahim et al. is the aerodynamic optimization of lone vehicles being detrimental to their performance while driving in close proximity [62]. Some of the numerical studies have also attempted to analyze the real-world implications on cooling, which has shown significant reductions in cooling flow and some increase in coolant temperature [63, 65, 66]. Finally, it has been shown that a shortened model can be used to generate a wake for the study of platooning experimentally, as the length of a wind tunnel test section is often limited [67].

2.4.4 Other related studies

As platooning can be simplified down to two or more objects in close proximity in a fluid flow, several studies using simplified bodies have yielded applicable insight into the flow physics, e.g., [68–70]. Some of these come from sports, some from train aerodynamics, and some are basic research studies. Telionis et al. investigated the usage of alternative methods for investigating vehicles driving in close proximity using a towing tank [71]. That study concluded that the drag and side forces change significantly when a car overtakes a truck, and large side forces are generated for the car. Jacuzzi et al. also attempted to improve the aerodynamics of vehicles in close proximity, such as race cars in drafting formation [72].

One of the most common areas in which traveling in close proximity is often applied is competitive cycling, where riders tend to group together to reduce the aerodynamic drag. Large reductions in drag were observed by Blocken et al. in smaller groups of cyclists [73] with a tendency of the drag to become more or less constant for the latter riders if the number of riders is greater than six. They also studied much larger groups of cyclists and showed that a drag reduction of up to 95% is possible [74], this is however not likely to apply to road vehicles in close proximity as this requires many riders side by side.

Perhaps the largest area of research relevant to platooning is the study of cargo trains, where the positioning of containers can greatly impact the aerodynamic resistance of the train. It has been shown that the gap between wagons is of great importance [75], that yaw conditions impact the slipstreaming effect negatively [76], and that a lower loading efficiency, equating to longer distances between containers, yields higher drag [77]. Some of the wake structures between containers have also been studied by Maleki et al. [78], which are similar to those found when two trucks are driving in close proximity. Li et al. also confirmed that the flow over a container is affected mainly by the upstream distance [75]. Maleki et al. has also shown that both RANS and URANS are inappropriate methods for analyzing the flow of bodies in close proximity [79].

Another area of study that is similar is the study of the tractor-trailer gap [80, 81], which exhibits similar behavior to two vehicles in very close proximity.

A further area that requires sound understanding for investigation of platooning, especially in experimental studies, is the Reynolds behavior of ground vehicles as well as the influence of moving ground simulation. It has been shown in many studies that the use of a moving ground simulation system can have a significant impact on the wake, especially for cars [82–87]. Other local changes to the flow [88, 89] and large effects on the absolute drag value obtained have also been observed [90]. Furthermore, some studies have shown slight changes to the Reynolds behavior of vehicles when a moving ground simulation is added [91, 92].

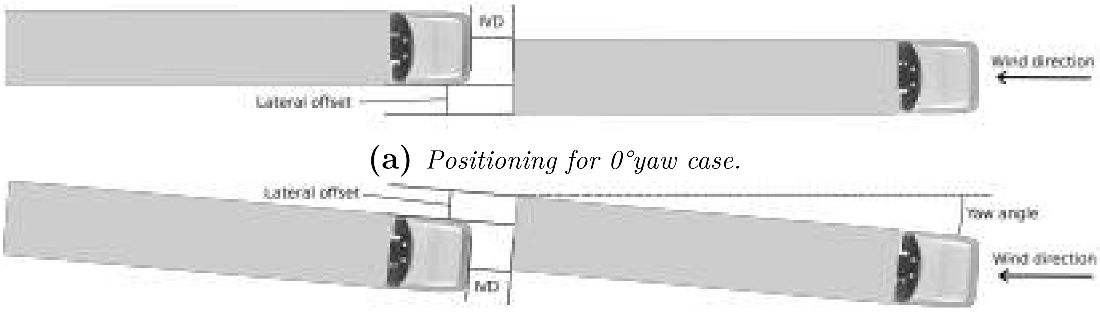
Finally, comparison between simulation results and wind tunnel experiments present several issues. Ljungskog et al. have investigated the influence of adding the wind tunnel to the simulations and found that the absolute drag values obtained improved significantly, however with no significant improvements to the prediction of deltas [93]. The same study concluded that there is a general lowering of pressures in the wind tunnel with some local larger changes to the pressure where large accelerations are present.

Chapter 3

Methodology

3.1 Definitions

To enable a clear discussion on platooning and its aerodynamic effects, some definitions are necessary. These relate to the positioning of the trucks in the convoy, the distance between them, the lateral offset, and the angle of the incoming flow, as shown in Figure 3.1. In this thesis, platoons consisting of two trucks have mainly been investigated, where the first vehicle is termed the leading truck and the second vehicle is termed the trailing truck. The spacing between them is taken as the distance from the rear-most part of the leading truck to the front-most part of the trailing truck and is termed the inter-vehicle distance (IVD). In this work, the IVD is limited to 0.5m to 30m (expressed in full-scale equivalent distances), as this was deemed a reasonable minimum and maximum value equal or lower than what is encountered on roads today. To further characterize the position of the truck, its lateral displacement is termed the lateral offset, and it is defined as the horizontal distance between the longitudinal centerlines of the two vehicles. As seen in Figure 3.1, the offset is in different directions depending on the yaw conditions —this was not intentional, but a simple misguided thought made during the experimental campaign. It is not expected to influence the results. In this study, the values have been limited to the corresponding space available in a single highway lane in Europe, which on average is roughly 3.6m, restricting the lateral offset to 1m, with a typical vehicle width of 2.6m. To further provide insight into the real-world behavior of vehicles driving in close proximity, side-wind conditions were also considered.



(a) *Positioning for 0°yaw case.*

(b) *Positioning for 5°of yaw case.*

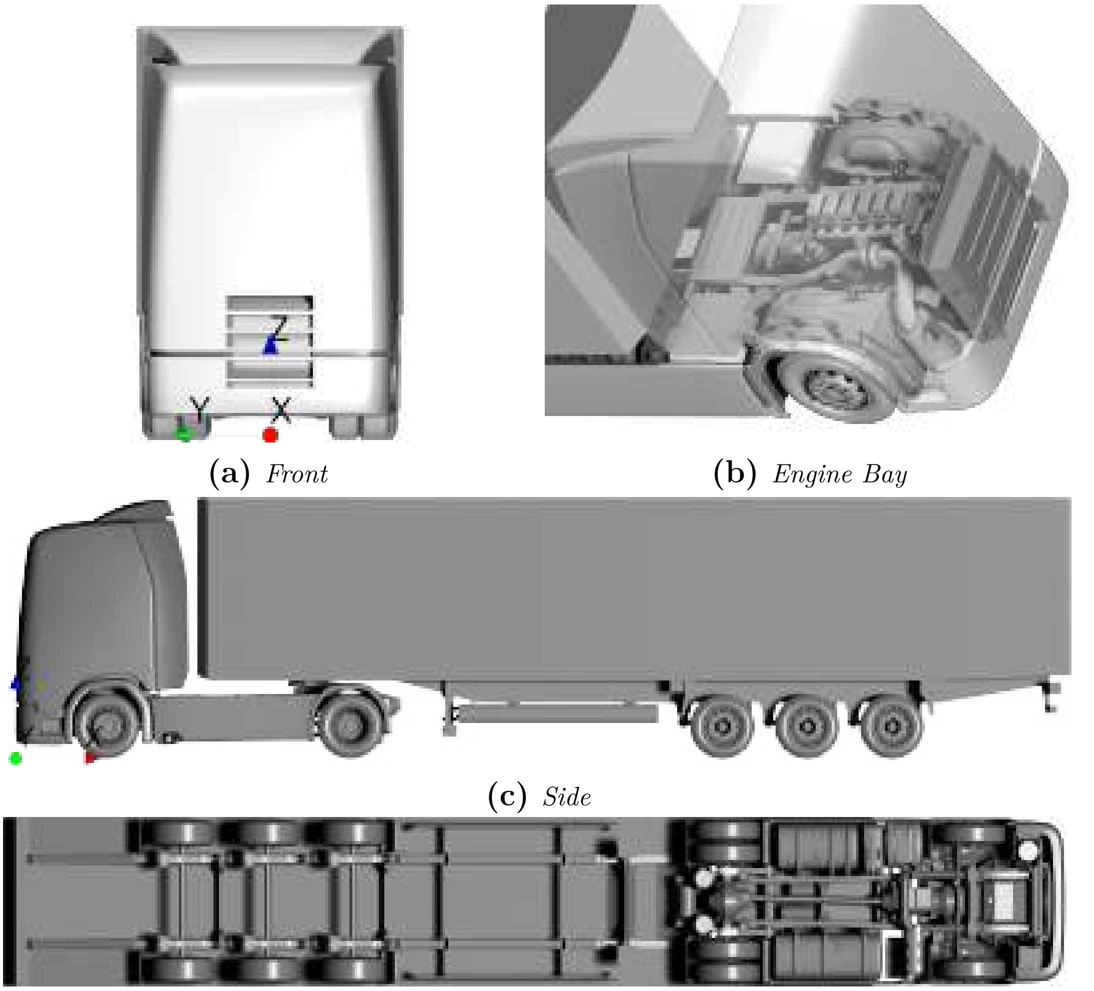
Figure 3.1: *Definition of the four position components; position, inter-vehicle distance, lateral offset, and yaw angle.*

3.2 Geometry

The geometries used in this thesis were a slightly simplified cab over engine (COE) style tractor combined with a three-axle trailer. The original model is 16.5m long, 4m tall, and 2.6m wide; the wind tunnel model is a 1/6th scale model. The simplifications made were defeaturing of internal geometries, e.g., no cables in the engine bay and a smoothed engine, and removal of small components. These were done to simplify the meshing and simulation of the models and decrease complexity for manufacturing. The external modifications made on the model are removal of split-lines and side-view mirrors; these are not expected to have an impact on trends seen in platooning. Rendered images of the models can be seen in Figure 3.2, showing the exterior, the engine bay, and the undercarriage. In the experimental portion of this thesis, a dummy model was used to create a representative blockage for the measurement model, of which forces were measured on. The tractor of this dummy model is identical to that of the measurement model, but the trailer undercarriage is simplified, consisting of a rectangle with added half circles to represent the wheels. The model has added side skirts, which should also minimize the impact of the simplified undercarriage.

Both the numerical and experimental models have cooling packages that are representative of those that exist on real trucks. The numerical cooling package consists of three porous regions with appropriate resistances for the three different coolers. In the physical models, the cooling package is represented by a combined mesh and honeycomb set to represent the behavior of a cooling package.

The physical models were instrumented with probes to measure the surface pressures. The measurement model was instrumented with time-resolved pressure sensors, while the dummy model was fitted with average pressure sensors. Figure 3.3 shows the location of the pressure probes, and the colors represent the surfaces of averaged pressure for the analysis. Although it would be of interest to know the



(a) *Front* (b) *Engine Bay*

(c) *Side*

(d) *Bottom*

Figure 3.2: *The tractor-trailer model used in this study.*

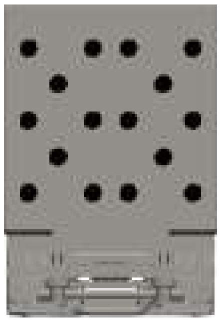
pressures on the front radii of the truck, no probes were installed on them. This was avoided to minimize the risk of induced detachment, as the radii are sensitive to separation. These pressure taps were instead added behind the radii and used to infer pressure changes on the corners.

3.3 Numerical method

3.3.1 Domain and mesh

The simulations were carried out using STAR-CCM+ version 2019.1 and 2020.2 with the $\kappa - \omega$ *SST* IDDES model using a hexahedral dominated unstructured

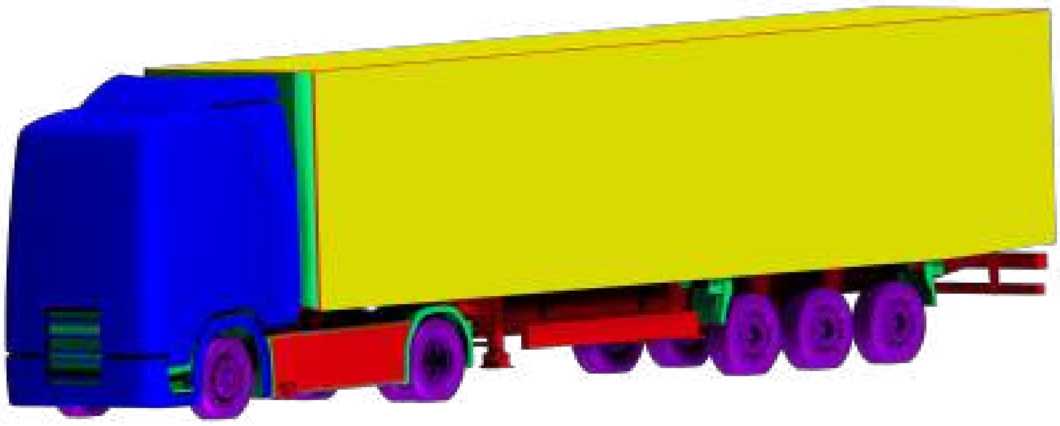
(a) *Front of the truck, the colors represent the different areas of surface averaged pressure. Black: roof, Green: front, Blue: right side, Red: tractor-trailer gap.*



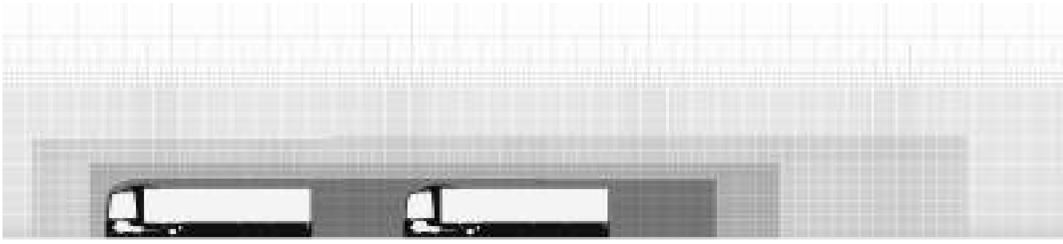
(b) *Base of the truck.*

Figure 3.3: *Pressure tap locations.*

grid with prism layers on the vehicle surface and ground. The implicit time-marching scheme was second-order accurate; a hybrid scheme using 85% central differencing and 15% second-order upwinding was used for convection. The domain size was 290.5m×104m×40m, corresponding to 5 vehicle lengths upstream, 10 vehicle lengths downstream, 40 vehicle widths wide, and 10 vehicle heights tall. This domain size was chosen to minimize the effects of boundaries and to allow for future simulations with lateral offset and yaw. The volume was then split into six different refinement volumes and the surfaces into five different sections per vehicle. The different levels are shown in Figure 3.4.



(a) *Levels of surface mesh size*



(b) *Section of the mesh at y=0*

(c) *Levels of volume refinement*

Figure 3.4: *Mesh strategy.*

These splits and levels were selected to capture the flow physics sufficiently while minimizing the number of elements used. The cell sizes used and the different meshes investigated are given in Table 3.1.

3.3.2 Convergence and solver settings

It is important to ensure sufficient convergence within each time step when using an implicit time discretization scheme. The simulations performed within this thesis used seven iterations per time step, allowing all residuals to drop well below 1e-3. The domain was flushed for 22s before any averaging was initiated to ensure

Mesh Resolution	Low	Medium	High
Base Size	40mm	30mm	20mm
Level 1	10mm	7.5mm	5mm
Level 2	20mm	15mm	10mm
Level 3	40mm	30mm	20mm
Level 4	80mm	60mm	40mm
Level 5	160mm	120mm	80mm
Level 6	320mm	240mm	160mm
Low y+ layers	12	12	10
High y+ layers L1	3	3	2
High y+ layers L2	4	4	3
High y+ layers L3	6	6	4
Wheel Mesh Size	20mm	15mm	10mm
Wheel layers	10	10	8
Cell Count (platoon)	150M	240M	460M

Table 3.1: *Refinement levels and number of prism layers for low, medium, and high mesh resolutions*

a fully developed flow-field. This flushing consists of 15s with a time step of 0.1s, followed by 5s at 0.01s, and finally 2s with the time step used in the averaging portion of the simulation. This final portion equals roughly one flow passage of the entire platoon at the longest IVD. The flow field and forces are then averaged for 10s following the flushing portion to ensure reliable and reproducible results.

Some solver instabilities can occur when utilizing an automated mesher with thin prism layers on complex geometries. A velocity-dependent smoothing was therefore implemented to improve the simulation stability. This was done by applying gradient smoothing to cells with a velocity higher than 100m/s at the end of each time step.

3.3.3 Boundary conditions

As the investigations in this thesis mainly pertain to a highway environment, the simulation boundary conditions were set to emulate this with a moving wall condition on the floor set to the same velocity as the inlet velocity of 25m/s. The outlet was set as a pressure outlet, and the walls and ceiling were set to zero-gradient boundaries. The surfaces on the vehicle were set as no-slip boundaries, and the wheels were given the appropriate rotational velocity. The cooling packs are simulated as porous regions with appropriate resistances, and the forces from these regions are included in the total C_DA.

3.3.4 X-ray plots

X-ray plots are used to ease the analysis of the numerical results and identify which areas of the trucks see changes in drag with changing conditions. These are created by setting up a grid in the x-y and x-z planes. The vehicle surfaces are then sorted into different bins that correlate to this grid, after which their individual forces are calculated and summed for each of the bins. Once this data is acquired, it is then subtracted from the corresponding configuration to produce a plot with differences in drag contributions. This data is displayed using surface plots, giving a fast and easy way to visualize areas of further investigation.

3.4 Evaluation of the accuracy of the simulation procedure

3.4.1 Mesh and time step resolution

$C_D A$ results for three different meshes are shown in Figure 3.5,where the changes between meshes for the leading truck are small. There are, however, larger differences for the trailing truck. Especially poor performance can be seen in the delta for the coarsest mesh between 5m and 10m IVD. This could be explained by an insufficiently resolved wake from the leading truck, causing changes in the oncoming flow for the trailing truck. As the main interests in this thesis are drag delta trends, a 30mm base size mesh (medium resolution) was chosen, as the deltas for this mesh agree well with those of the highest resolution mesh. The computing resources required are roughly halved for this mesh compared to the finest, providing for the possibility of more simulations.

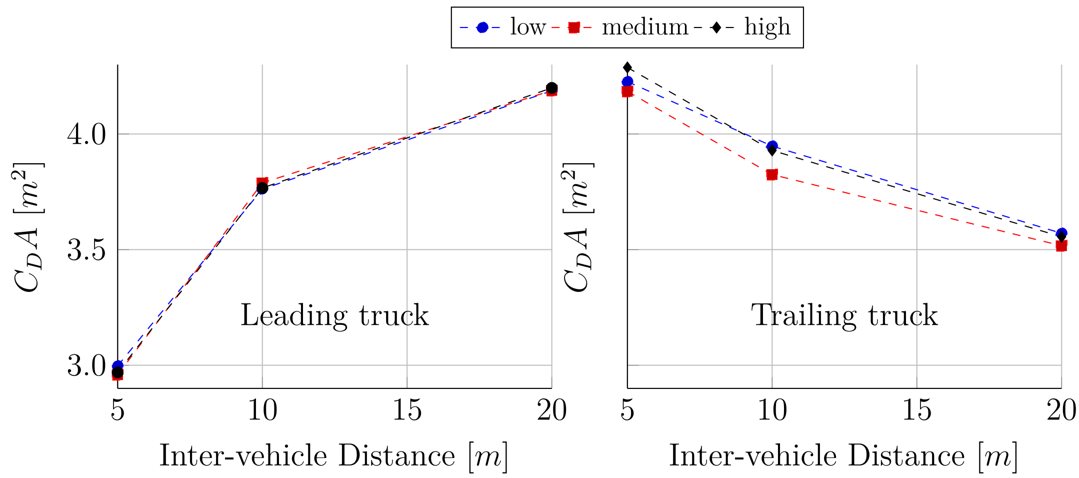


Figure 3.5: *$C_D A$ v inter-vehicle distance for three different mesh resolutions.*

A study of the time resolution required was performed by running the same simulation with four different time step lengths: 1.6ms, 0.8ms, 0.4ms, and 0.2ms. This study was conducted with an IVD of 10m as this is a distance where the two trucks have shown to have similar drag figures. These results are presented in Figure 3.6, and show that decreasing the time step below 0.8ms does not yield any large changes in drag. Therefore a time step of 0.8ms was used in all simulations in this thesis.

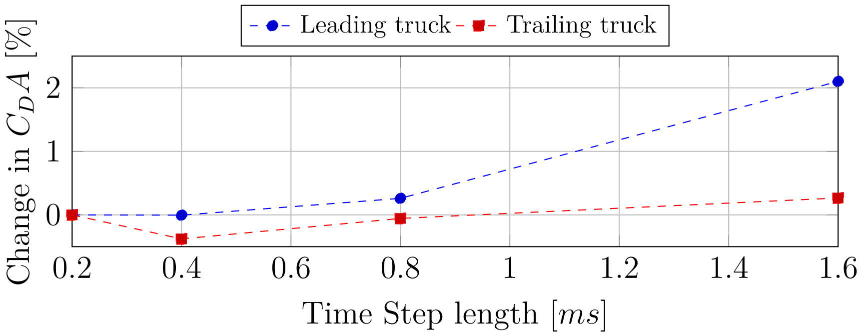


Figure 3.6: *C_DA v time step length.*

3.4.2 Averaging time

Sufficient averaging time is required to ensure reliable forces and flowfields; however, the minimum viable averaging time should be used as the computational time increases linearly with it. There are several ways to ensure that this is the case and two of them have been considered in this thesis. The first one is described in Eq. 3.1 and represents the standard deviation of a moving mean of C_DA.

$$\sigma_i = \sigma\left(\sum_{j=n}^{n+i} C_{D,j}\right), n = 1, 2, 3, ..., k-i, i = 1, 2, 3, ..., k \tag{3.1}$$

The results from this analysis are shown in Figure 3.7 and imply that an averaging time of 8s is sufficient for a low standard deviation for the leading truck. This is true for the trailing truck as well, although the standard deviation is somewhat higher. This method of analysis is not very useful close to an averaging time of 10s, as the number of samples decreases when the averaging time becomes longer. However, some data can be inferred from the lower end of the graph by extrapolating the trends. This extrapolation would yield an uncertainty that is well below 5 C_DA counts (roughly 0.12% of the total drag) with an averaging time of 10s. This is significantly smaller than the expected changes seen in a platooning scenario and is thus deemed acceptable.

Additionally, Eq. 3.4.2 was used to estimate the uncertainty of the mean value

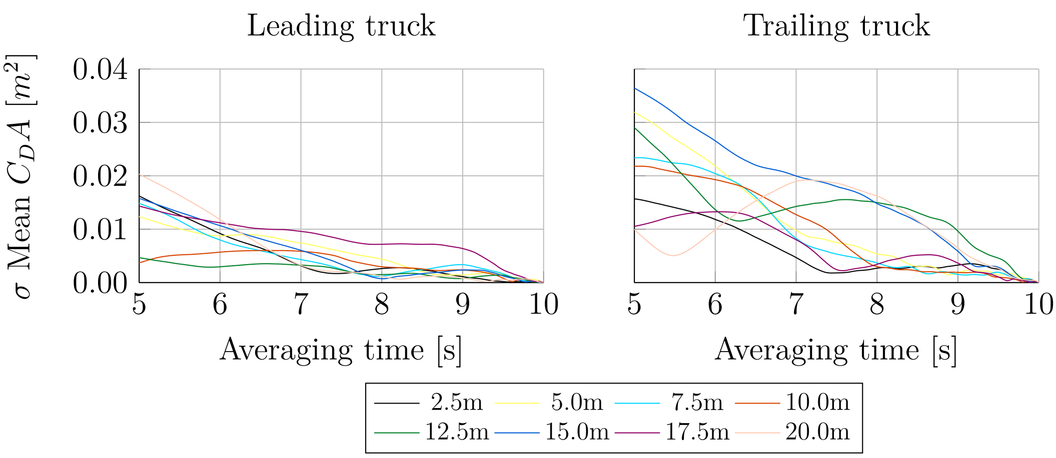
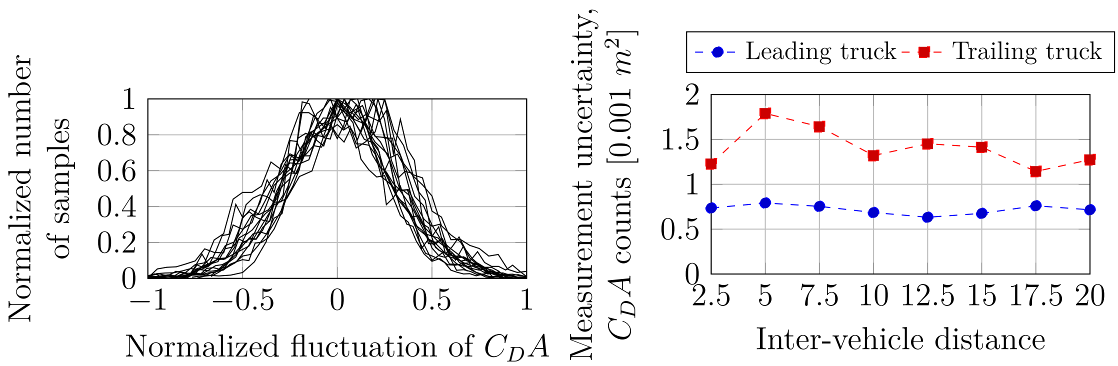


Figure 3.7: *Uncertainty of final C_DA as a function of averaging time.*

if the force fluctuations were normally distributed and random (see Figure 3.8a).

$$\Delta F_{avg} = \frac{\sigma}{\sqrt{n}} \tag{3.2}$$

The uncertainty for both trucks as a function of IVD is shown in Figure 3.8b; where the averaging time used was 10s. The drag fluctuations are significantly larger for the trailing truck, thus yielding a greater uncertainty. Further, the uncertainty is slightly higher for lower IVDs, except for the 2.5m case. This is likely due to a larger influence of the leading truck's wake as the distance decreases. The stabilized effect seen at 2.5m is believed to be due to a change in flow structures leading to smaller fluctuations.



(a) *Normalized C_DA fluctuations v number of times they occur, showing a normal distribution of force fluctuations around the mean drag value*

(b) *Uncertainty of C_DA value measured in 1/1000 C_DA.*

Figure 3.8: *Standard deviation of mean C_DA versus time of averaging.*

3.4.3 Flow field analysis

Model derived values

To investigate the validity of the present simulations, the turbulent viscosity ratio (TVR), the IDDES blending factor, and the Courant-Friedrichs-Lewy (CFL) criteria were analyzed and presented in Figure 3.9. As seen in Figure 3.9a, there are no significant jumps in the TVR, and the values are reasonably low in most areas except close to the truck surfaces and ground. These higher TVR values are expected near surfaces as these areas are handled by URANS in the IDDES model used. This is visible in Figure 3.9b where the model switches quickly to LES mode outside areas close to the truck surface. Furthermore, the areas close to the surface are shielded by the IDDES model and remain in URANS mode. Finally, the CFL number is around 1 or lower, in most areas, except where large accelerations in the flow occur, see Figure 3.9c. Ekman et al. [94] have shown that for scale resolving simulations using an implicit time marching scheme, a CFL number of up to 20 is acceptable even if a high degree of accuracy is required. The values presented here are well within this requirement.

(a) *Turbulent viscosity ratio*

(b) *IDDES blending function indicating which mode is used: 0 being LES and 1 URANS*

(c) *CFL number, instantaneous values*

Figure 3.9: *Cut planes at y=0 showing TVR, IDDES blending factor, and CFL for a 2.5m inter-vehicle distance.*

Resolved turbulent kinetic energy ratio

$$k_{\%res} = 100 * \frac{k_{res}}{k_{res} + k_{mod}}, \quad k_{res} = \frac{1}{2}(u_i' u_i'). \tag{3.3}$$

To ensure that the mesh is sufficiently refined for the simulation, the percentage of resolved turbulent kinetic energy is computed in Eq. 3.3. Pope [95] suggests that this metric should be above 80% for a well-resolved LES; this is shown to be true outside the boundary layers in Figure 3.10.

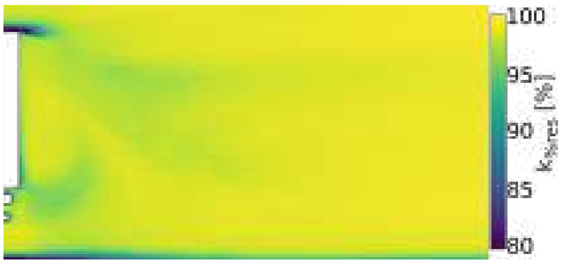


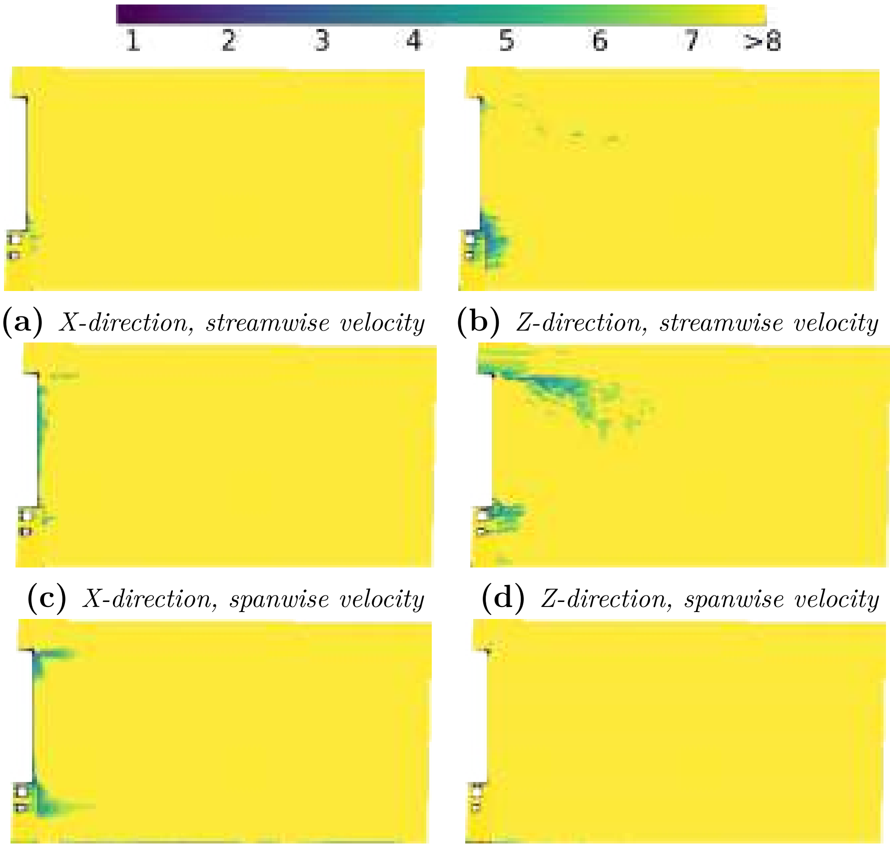
Figure 3.10: *Percentage of total kinetic energy that is resolved for the wake at y=0.*

Two-point correlation

To further assess the validity of the mesh used in this thesis, a two-point correlation investigation was performed for a plane along the symmetry line of the wake of an isolated truck. This type of analysis has previously been used in [96, 97] and provides a better measurement of mesh resolution of an LES-type simulation than the energy spectra or the resolved turbulent kinetic ratio [95] presented in the previous section. The normalized two-point correlation is defined in Eq. 3.4 and calculated for all points in the plane.

$$C_{u_i u_i}(x_1, x_2) = \frac{\overline{{u_i}'_{x_1} {u_i}'_{x_2}}}{u_{i\,rmsx1}^2} \tag{3.4}$$

Figure 3.11 shows the number of cells having a normalized correlation of 0.1 or greater. The graphs were split up into correlation in the x and y direction for the different velocity components. The value of 0.1 was chosen to indicate that there was no longer any correlation between the two points as it would not be feasible to assess correlation for each point manually. According to Davidsson [98], a minimum of 8 cells is recommended to be correlated for a coarse LES. This is shown to be true for most cells in the wake except for the span-wise velocity in the z-direction, figure 3.11d, where the correlation in the top shear layer of the wake is poor. These deficiencies are attributed to the small scale of the span-wise structures present in the shear layer not being sufficiently captured by the mesh. There are further small areas of insufficient correlation around the anti-intrusion bars underneath the trailer as well as near the surface of the trailer. These are not expected to significantly impact the results of the simulations as these areas are not a primary point of interest.



(a) *X-direction, streamwise velocity* (b) *Z-direction, streamwise velocity*

(c) *X-direction, spanwise velocity* (d) *Z-direction, spanwise velocity*

(e) *X-direction, vertical velocity* (f) *Z-direction, vertical velocity*

Figure 3.11: *Two-point correlation: Number of cells until the correlation drops below 0.1 for the wake at y=0.*

3.5 Experimental method

3.5.1 Wind tunnel

The experimental portion of this thesis was carried out in the Volvo Cars Aerodynamic wind tunnel. This tunnel is a slotted wall wind tunnel with a cross-sectional area of $27.1m^2$ and a slot open ratio of 30%. The tunnel is equipped with a ground simulation and boundary layer control system consisting of a suction scoop, distributed suction, and tangential blowers behind each of the five belts. The distributed suction system consists of a perforated floor with two portions; the part in front of the turntable has an open area ratio of 8.9% and the portion on the turntable has an open area ratio of 4.5%. The five-belt system consists of four wheel-drive units and a center belt which is 5.3m long and 1m wide—roughly twice as long and wide as the truck model used. Forces are measured through an underfloor balance capable of repeatability below 0.5% for a single isolated model.

An outline of the wind tunnel test section is shown in Figure 3.12. The light green area in this figure represents the space that was occupied by the models, the red filled area represents the area covered by the measurement model, and the outlined red rectangles represent two examples of positions for the dummy model. The maximum IVD investigated in this thesis was 30m, and the maximum yaw angle was 5°. This yaw angle was chosen given fairly strict limitations of the time available in the wind tunnel and is usually a good approximation for the wind averaged drag for a COE truck. The wind averaged drag usually deviates less than 1% from the drag value measured at 5° yaw [99]. For further information on the wind tunnel, its ground simulation system, and flow quality see [96, 100].

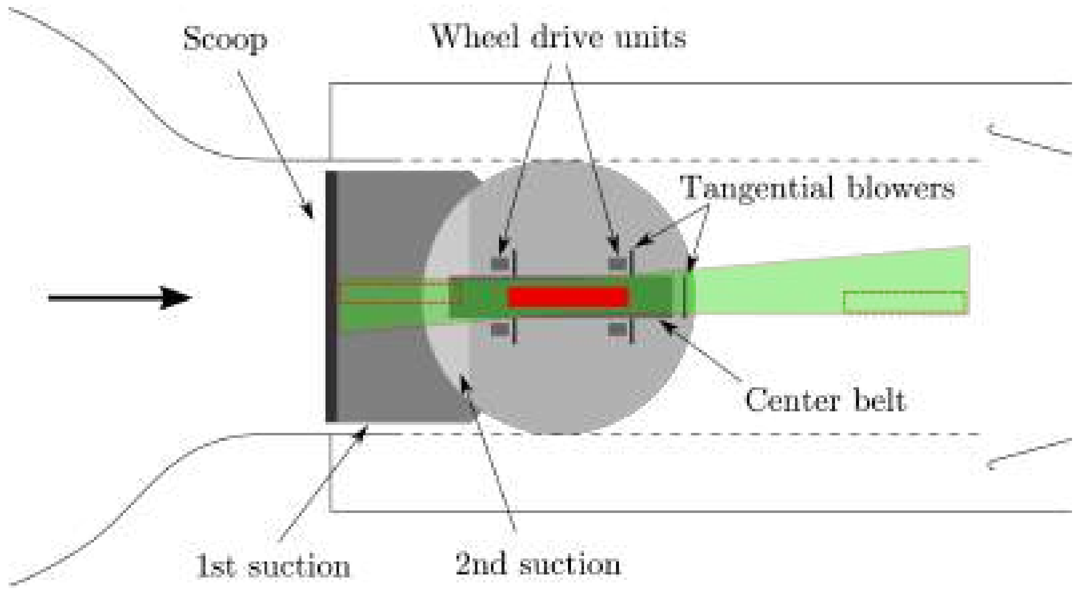


Figure 3.12: *Layout of the ground simulation system and the available space in the test section for varying IVD, lateral offset, and yaw.*

3.5.2 Experimental setup

To enable experimental investigations of platooning in a wind tunnel, scale models have to be used. This means that for the wind tunnel used in this study, a custom mounting solution and experienced personnel were required for safe operation on the moving belt. As the model itself and the belt were unable to support the full weight of the model, it had to be suspended from the ceiling.

Figure 3.13: *Mounting solution. Here, the leading truck is the dummy model, and the trailing truck is the measurement model.*

This was done by mounting a steel beam to the ceiling of the wind tunnel from which two 6mm steel cables were attached and then ran through model's roof to the model's internal beams (see Figure 3.13). This suspension of the model has the benefit of enabling use of the wind tunnel's existing balance as the cables hang vertically and will thus not absorb the forces experienced by the model. However, as the model is not constrained in the ground plane with these wires, it also had to be attached by 6mm steel cables to the existing restraint posts of the wind tunnel. These posts are usually fastened to the vehicle being tested in the wind tunnel and are connected to the balance below the floor. This is how forces were measured in this experiment. These cables will have an impact on the drag measured on the vehicle; however, this has been neglected, as the main interests in this study were the differences between configurations and not the absolute values. Moreover, roughly half of the drag force generated by the wires should be absorbed by the mounting solution in the ceiling. The total frontal area of the wires is less than 10% of the frontal area of the trucks.

As the center belt drives the wheels of the truck and the belt is not attached to the balance, the rolling resistance had to be removed from the total drag. This was done by setting the center belt to the correct speed with the wind off and taring the balance before the wind is turned on for each force measurement. These rolling resistance values should remain correct even if the model moves slightly due to aerodynamic forces as the wheels are free-floating in the vertical direction.

The dummy model was resting on the floor and held up by itself and restrained in the ground plane by 6mm cables to existing holes in the floor. When the dummy model was placed over the center belt, it had to be held away from the belt to avoid damage to both the belt and the model. This was done by inserting a 20mm thick beveled beam underneath the wheels of the dummy model. This difference in height could potentially have an influence on the results; this is, however, disregarded as there was no other solution available at the time of the test.

All wheel-drive units were run at the corresponding wind speed to minimize the drag generated by them, as they are directly attached to the balance. Furthermore, two different modes were used for the boundary layer control system, as when the dummy model is placed in front of the measurement model it stands on the distributed suction area. The first configuration used was only utilizing the suction scoop; this mode was used when the dummy model stood on the distributed suction area, which was the case when placed in front of the measurement model. When the dummy model was positioned behind the measurement model, both the suction scoop as well as the distributed suction system were used. The tangential blowing system was not used for any configuration, as it was deemed unnecessary as well as to ease future comparisons with numerical simulations.

Chapter 4

Results

This section of the thesis will give a summarized view of the results. For a deeper discussion and analysis of the results see the included papers. First, a section on the validity of the experimental results is given, which is then compared to the numerical results. Following this, a section on the behavior of two trucks in tandem with respect to IVD will be given, where CFD results will be used to further analyze the changes in drag. Then a section on the behavior of a platoon of two trucks with varying IVD, yaw, and lateral offset. All forces are normalized to ease comparisons between the different experimental configurations as well as computational results. The force normalizations are done toward their respective isolated truck values: distributed suction on for the leading truck forces, and off for the trailing truck forces, for their respective yaw angle. CFD values are normalized toward forces from a simulation of an isolated truck. The only force values that are not normalized toward this are those of the Reynolds independence study, where they are normalized to the drag value at the highest Reynolds number. All IVDs and offsets in the results section are given in full-scale equivalent distances.

4.1 Validity of the results

4.1.1 Reynolds independence of the experimental study

It is necessary to ensure scalability in terms of size and velocity to produce experimental results viable for use in real-world scenarios. This is most easily accomplished by ensuring that the experiments performed are performed at sufficiently high Reynolds numbers (Figure 4.1).

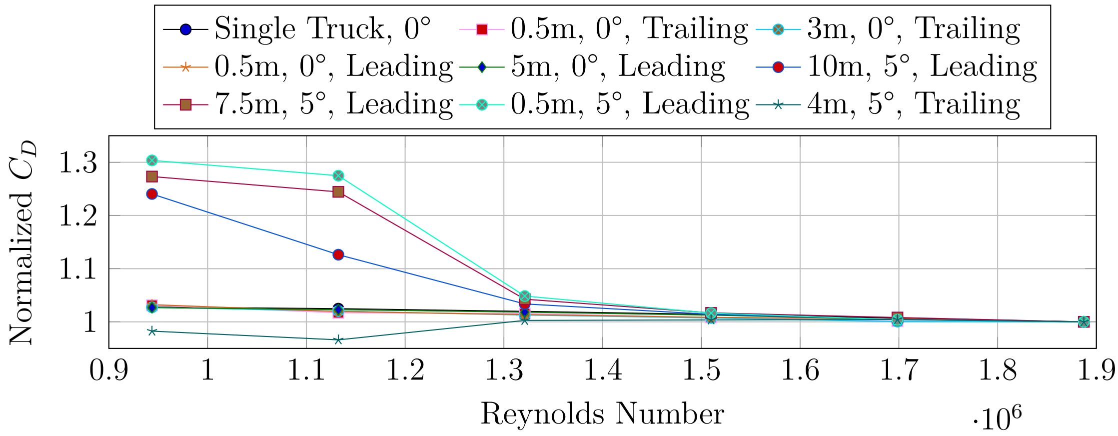


Figure 4.1: *C_D versus Reynolds number, legend denotes "Inter-vehicle distance, yaw angle, position of truck". Normalized C_D is defined as C_D divided by C_D for the highest velocity of that configuration.*

This was ensured by performing several Reynolds sweeps throughout the campaign, which showed that the drag for a single and two-truck platoon at zero yaw practically does not change with an increase in Reynolds number. In yaw conditions, there is a large sensitivity to Reynolds number below roughly 1.5e6. However, as the Reynolds number is increased from 1.7e6 to 1.9e6 there is almost no change in drag (0.05%-0.8%). This strong Reynolds dependence is believed to be due to detachment at the front edge rounding on the leeward side, which can be inferred from Figure 4.3, where a large decrease in high-frequency fluctuations can be seen as well as a large decrease in pressure on the leeward side, Figure 4.2, as the Re is increased from 1.1e6 to 1.3e6.

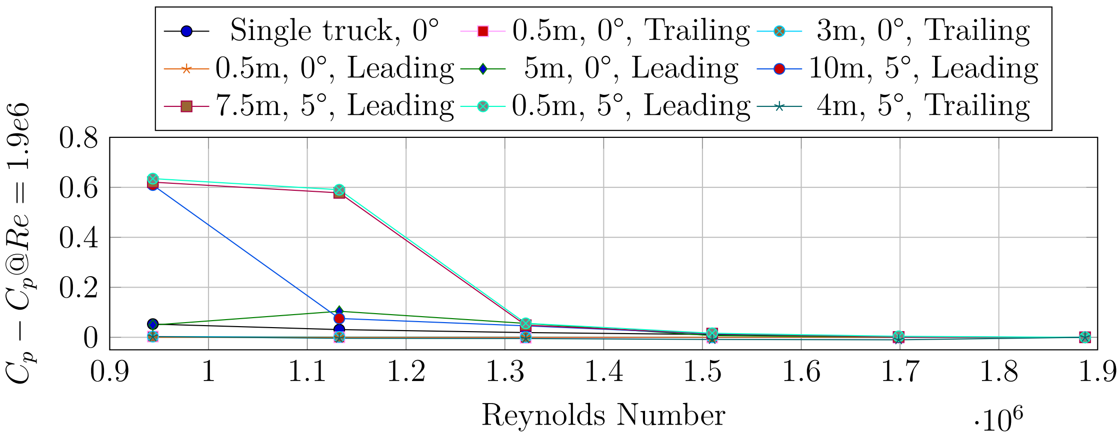


Figure 4.2: *C_p minus C_p at Re=1.9*10^6 versus Reynolds number for a point behind the leeward corner of the tractor.*

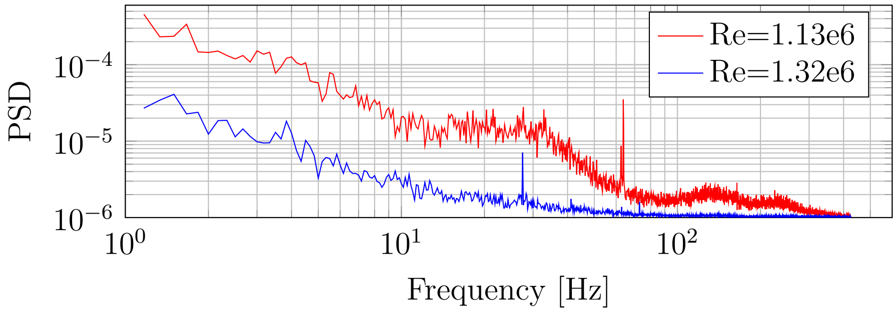
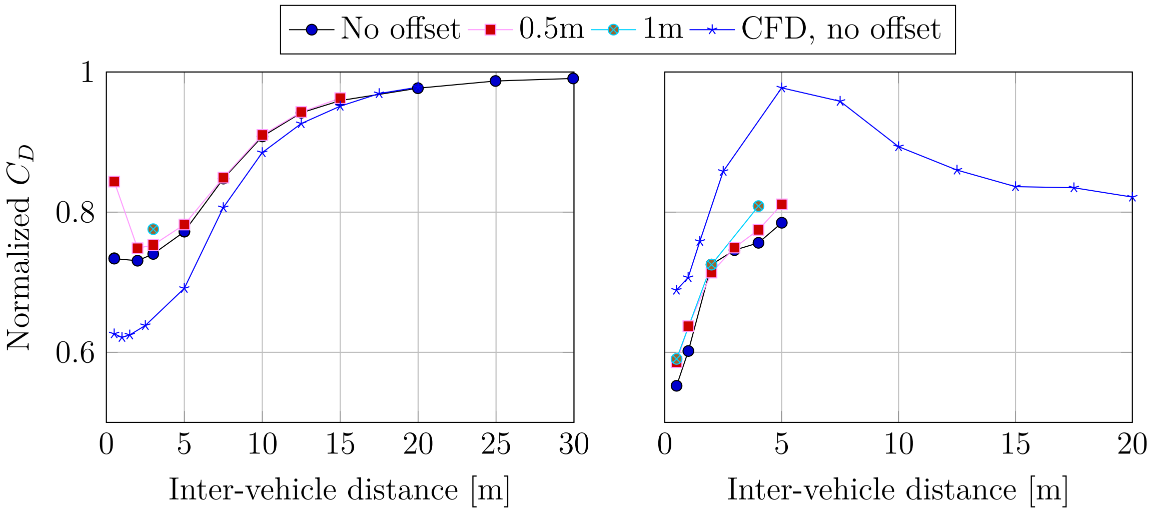


Figure 4.3: *Frequency spectra at a point behind the leeward corner for the leading truck at a 0.5m IVD and 5°yaw.*

4.1.2 Comparison of CFD and experimental data

A comparison has to be made to assure sufficient accuracy to enable proper usage of CFD results to analyze the experimental results. Figure 4.4 shows the drag for different IVDs of both the experimental and numerical studies. However, the two studies show similar trends with some differences in the magnitude of change, as shown in Figure 4.4. Nevertheless, for the trailing truck, an underestimation of drag is seen. It is important to recognize that the two studies use different normalization values and the drag values seen in the two methods are significantly different.



(a) *Leading Truck* **(b)** *Trailing Truck*

Figure 4.4: *Normalized C_D versus inter-vehicle distance with and without lateral offset. Zero yaw*

When investigating the sources of these differences in drag reduction, it is important to realize that there can be an offset in pressure values between wind

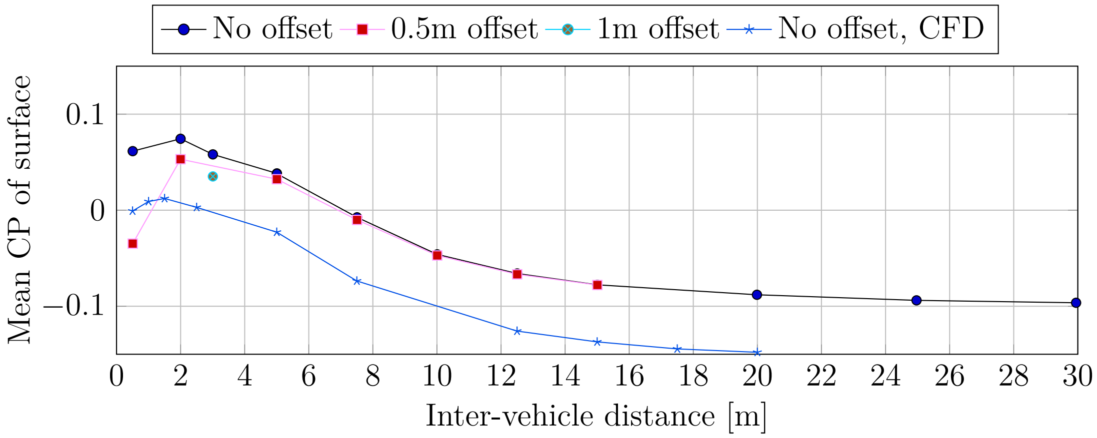


Figure 4.5: *Average base C_P for the leading truck versus inter-vehicle distance with and without lateral offset.*

tunnel and numerical studies of open road scenarios [96]. This is observed in Figure 4.5, where the base pressures of the CFD results are generally lower than those of the experimental study. It can, however, be seen that the trends are very similar between the two methods, with a similar discrepancy in the pressure deltas seen in the forces. This discrepancy could be due to the mesh of the numerical setup. Nevertheless, this has not been investigated yet.

The trailing truck has a more complex flow and mechanism for changes in drag in a platoon, and it is thus more difficult to find the source of the difference in drag. However, Figure 4.6a shows that the deltas for most configurations agree well between CFD and experiments. Some of the pressure locations show larger discrepancies in the deltas between longer and shorter IVDs, such as the pressure on the front of the truck as well as the pressure in the tractor-trailer gap. The discrepancy of the pressure at the front face is likely connected to the pressure at the base of the leading truck. This is something that will have to be investigated in the future. The changes seen in the tractor-trailer gap are not as simple to discern the origins of as it could be a slight difference in how the roof deflector is angled or simply a difference in the flow between the vehicles.

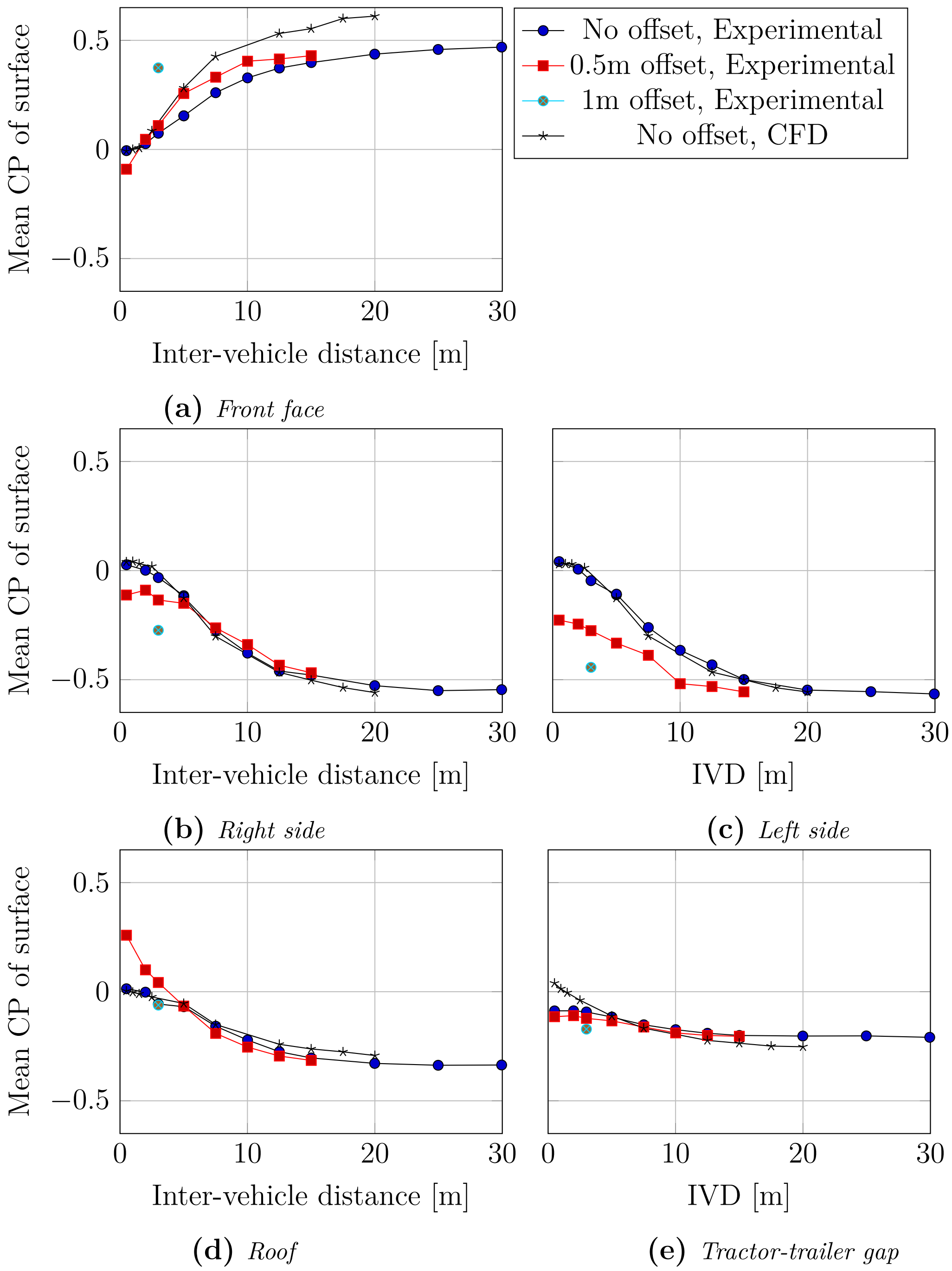


Figure 4.6: *Average C_P on the different surfaces on the front of the trailing truck versus IVD with and without lateral offset, zero yaw.*

Although there are some discrepancies seen in the pressure and force deltas between the two methods, usage of the CFD results to gain further insight into the behavior of the system is still deemed viable. This is the case as the differences are relatively small, and the trends are very similar in most configurations. Therefore, only the global force and surface pressure measurements obtained experimentally will be shown hereafter, and CFD will be used to gain further insight into the mechanisms of change.

4.2 Zero yaw

4.2.1 Leading truck

It can be seen in Figure 4.4a that there is a general trend toward lower drag as the IVD decreases for the leading truck, with a higher rate of reduction between 3m and 10m. This reduction can also be seen to correlate well with the decrease in base pressure, Figure 4.5. It can also be seen that at medium to longer IVDs, there is only a slight sensitivity to lateral offset, whereas, at short IVDs there is a greater sensitivity. To further understand this behavior, the drag development over the truck from numerical results is plotted in Figure 4.7 where it is visible that the vast majority of the changes in drag occur at the base of the leading vehicle, with some slight changes on the underbody of the trailer.

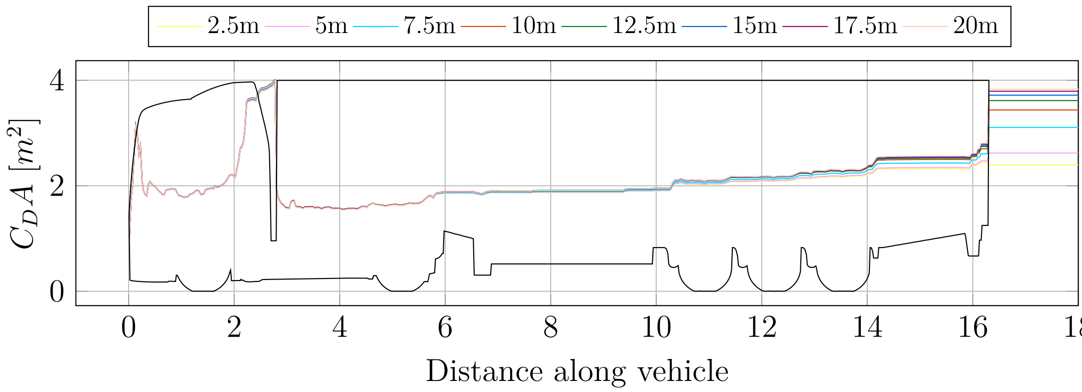
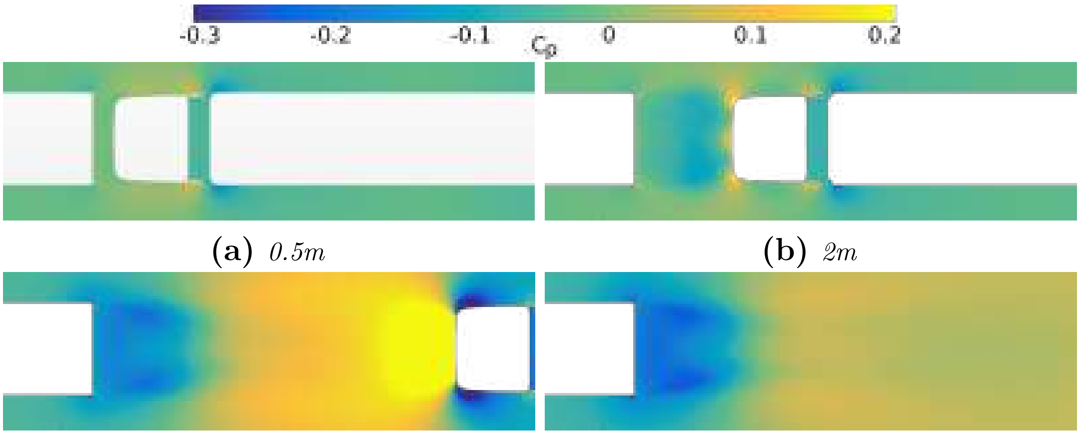


Figure 4.7: *Leading truck, CdA vs x*

This has been reported in many other studies and is thought to be due to the high-pressure region created by the stagnation pressure of the trailing vehicle. The pressure between the vehicles is shown in Figure 4.8, where it can be seen that the pressure decreases gradually between the two trucks as the IVD is reduced.

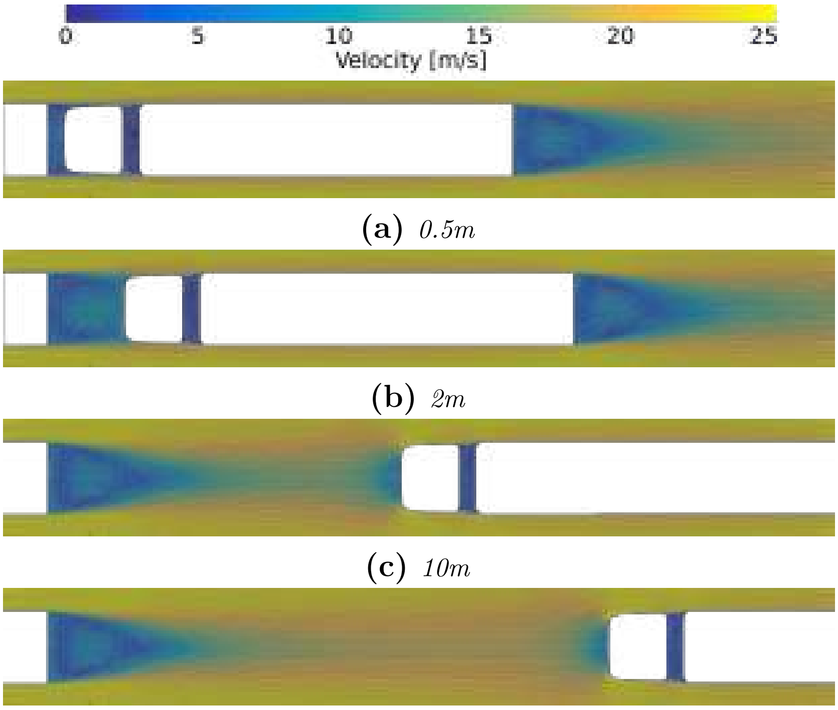


(a) *0.5m* **(b)** *2m*

(c) *10m* **(d)** *20m*

Figure 4.8: *Time-averaged C_p distribution in between vehicles at z=2.5m. Results obtained from CFD simulations.*

The velocity field is shown in Figure 4.9 and shows that there are only minimal changes to the wake of the leading vehicle for greater IVDs. This does not hold true when the distance becomes small, as significant changes to the velocity field occur where the wake is transformed into two symmetrical vortices that get deformed at the very shortest IVD. This change in the flow field causes a slowdown of the increasing pressure and thus decreases the rate of drag reduction with IVD.



(a) *0.5m*

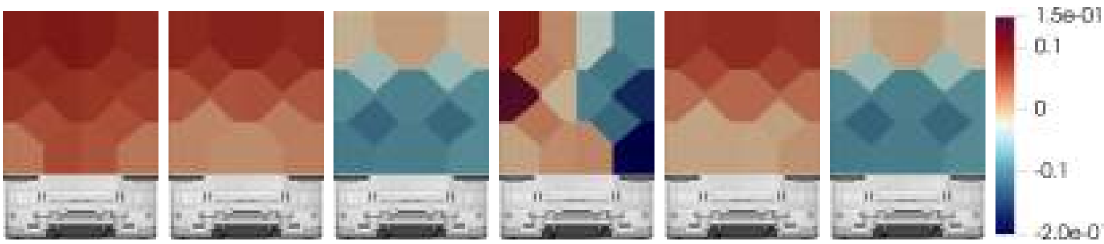
(b) *2m*

(c) *10m*

(d) *20m*

Figure 4.9: *Velocity magnitude between the two trucks with in-plane streamlines at z=2.5m. Results obtained from CFD simulations.*

The reason for the low sensitivity to lateral offset for the leading truck at longer IVDs is believed to be due to the wide area of relatively higher pressure radiating from the trailing truck's stagnation area. This change in pressure, both in the streamwise direction as well as in the spanwise direction, is shown in Figure 4.8c. The uniformity of the pressure in the spanwise direction decreases as the distance decreases from the trailing truck, and for very short distances, the area of high pressure is narrow laterally.



(a) *0.5m* (b) *5m* (c) *12.5m* (d) *0.5m* (e) *5m* (f) *12.5m*

Figure 4.10: *Base C_P of the leading truck, a-c is with 0m offset and d-f is with 0.5m offset at zero yaw. The values denotes IVD.*

Figure 4.10 shows that the pressure becomes more uniform as the IVD decreases when no offset is present. It can also be seen that the pressure in the lower part of the base increases more than the upper part of the base. This has been observed in simulations where the pressure at the lower part of the wake increases faster than the top end of the wake. This is most likely caused by the low ground clearance of the trailing vehicle, yielding a greater blocking effect at the lower part. This also has the effect of lifting the wake of the leading truck as the IVD decreases to short distances. An additional cause for the larger sensitivity to lateral offset at an IVD of 0.5m can be seen in Figure 4.10, where there is a drastic decrease in base pressure on the exposed rear part of the leading truck. This is thought to be caused by the exposed part acting like a backward-facing step at the very short distance.

4.2.2 Trailing truck

Compared to the leading truck, the trailing truck presents many more affected areas and the changes are more intricate. As seen in Figure 4.4b, the changes in drag produce a local maxima, which is something that has been observed in many other studies, e.g., [36, 40, 43, 47–50]. The drag buildup is plotted for the trailing truck in Figure 4.11 and shows that the majority of the changes occur at the front of the vehicle, specifically at the front edge and in the tractor-trailer gap.

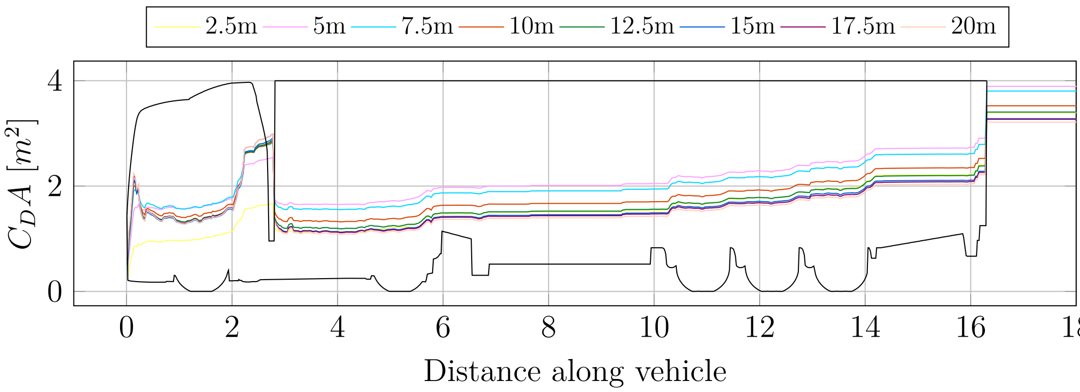


Figure 4.11: *Trailing truck, CdA vs x*

To further narrow down the source of the changes, an X-ray plot is used, Figure 4.12. It shows that the majority of the changes come from three major areas; the front stagnation area, front edge rounding, and the tractor-trailer gap. The only one of these three affected areas that works to reduce the drag is the reduction in stagnation pressure; the other two increase the drag experienced by the trailing truck. These changes can clearly be observed in Figure 4.6, where the pressure on the front edge rounding as well as in the tractor-trailer gap increases as the IVD decreases. It is also seen in the drag curve that the front face pressure and front edge rounding pressures start decreasing rapidly at roughly the same distance,

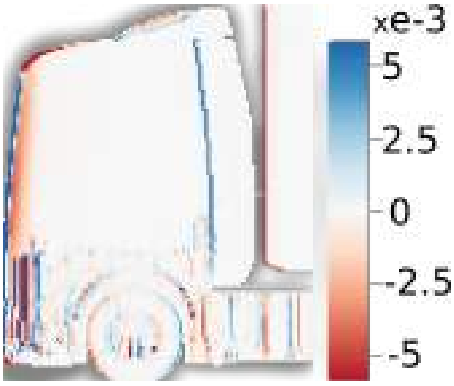
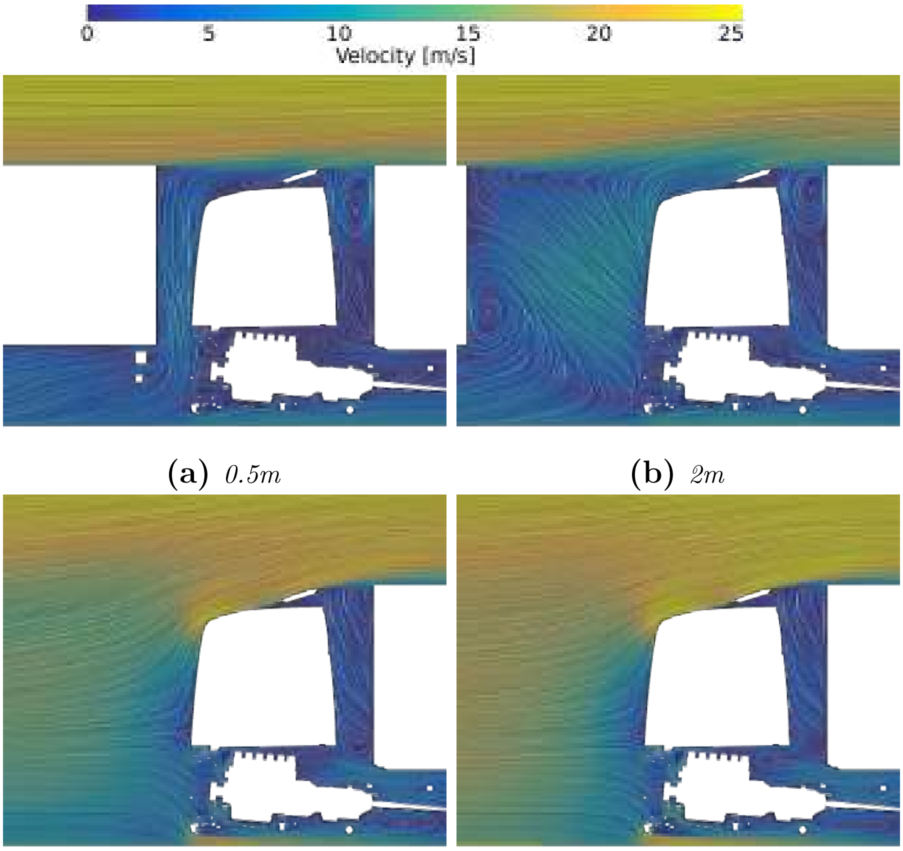


Figure 4.12: *Trailing truck difference in drag between 20m and 2.5m*

15m. Notably, the drag remains fairly stable, and the drag development remain similar after these two features. At lower distances than this, the drag development becomes slightly higher after these features. Additionally, the drag after the tractor-trailer gap increases as the distance decreases down to 5m. Further, the drag for the shortest distance is very low past the radii, owing to the very low production of drag at the front face of the truck. However, the drag increase over the tractor-trailer gap is by far the largest for this distance. The reason for the changes in pressure at the front face of the truck is apparent in Figure 4.9 where the velocity at the front of the trailing truck decreases as the IVD is reduced. For very short distances, the formation of two vortices further reduces the pressure at the truck's front. As for the pressure at the front edge rounding, similar effects cause the increase in pressure. At short IVDs, there is a slight impingement from the closing wake of the leading truck, further increasing the pressure at the radii. The last and most complex phenomena affecting the drag of the trailing truck were the increased pressure in the tractor-trailer gap, which more difficult to see in Figure 4.9, where only the effect of changing flow structures in the gap can be seen. The velocity is therefore plotted in the x-z plane in Figure 4.13. It can also be seen that there is a vortex formed at the top of the tractor-trailer gap with some impingement at the top edge of the trailer. This vortex forming can also be seen when the air deflector at the roof is set too low. The reason for this impingement at the leading edge of the trailer is believed to be due to the reduced oncoming flow energy as well as a slight downwash of the wake of the leading vehicle.

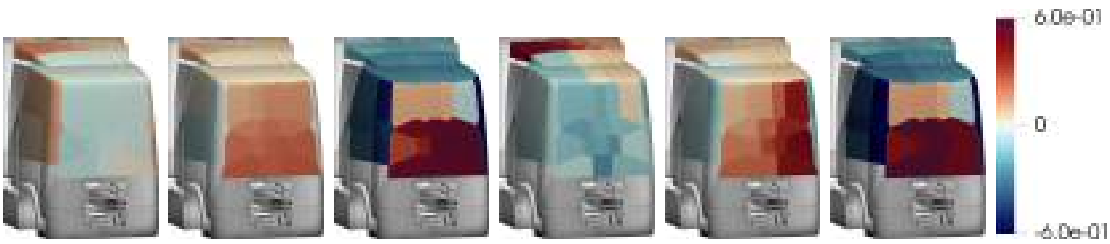


(a) *0.5m* (b) *2m*

(c) *10m* (d) *20m*

Figure 4.13: *Time-averaged velocity distribution in between vehicles at centerline. Results obtained from CFD simulations.*

As shown in Figure 4.4b, the trailing truck is more sensitive to lateral offset at longer IVDs than the leading truck. This is due to the different mechanisms of drag reduction experienced by the two vehicles, where the leading truck is mainly affected by changes in pressure, whereas the trailing truck is mainly affected by changes in the oncoming flowfield.



(a) *0.5m* (b) *5m* (c) *12.5m* (d) *0.5m* (e) *5m* (f) *12.5m*

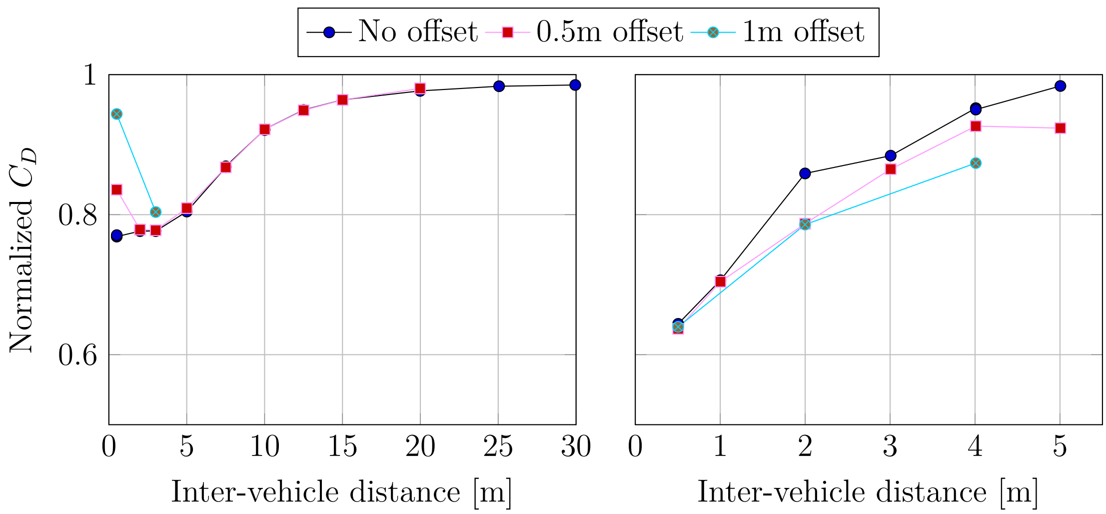
Figure 4.14: *Tractor C_P of the trailing truck, a-c is with 0m offset and d-f is with 0.5m offset at zero yaw. The values denotes IVD*

It can be seen in Figure 4.14 that the pressure tends to become more uniform as the IVD decreases. Furthermore, the pressure at the front face becomes less uniform when a lateral offset is added, as expected when the vehicle is shifted out of the wake of the leading truck. The exposed corner also sees different effects depending on the IVD, where at short IVDs there is hardly any change observed when increasing the distance, and at longer IVDs it tends to follow the same behavior as without any lateral offset. This is potentially due to the trailing truck entering the wake of the leading truck forming a cavity that might not be as sensitive to the spacing. It can also be seen that the pressure in the tractor-trailer gap hardly changes for small offsets except for IVDs shorter than 5m, where a small difference can be noticed.

4.3 5 degrees yaw

4.3.1 Leading truck

Figure 4.15a generally shows higher relative drag than that of Figure 4.4a and lower deltas between the different IVDs. This lower performance of vehicles driving in close proximity has been shown in similar cases previously and is expected as the trailing truck's stagnation point moves when it is subject to yaw conditions. As the lateral offset direction is toward the leeward side, lower sensitivity to lateral offset is to be expected, and it can be seen that there is almost no sensitivity, except at the very shortest IVDs. The corresponding differences are shown in Figure 4.16, where the base pressure is generally slightly lower at yaw.



(a) *Leading Truck* **(b)** *Trailing Truck*

Figure 4.15: *Normalized C_D versus inter-vehicle distance with and without lateral offset. 5°yaw*

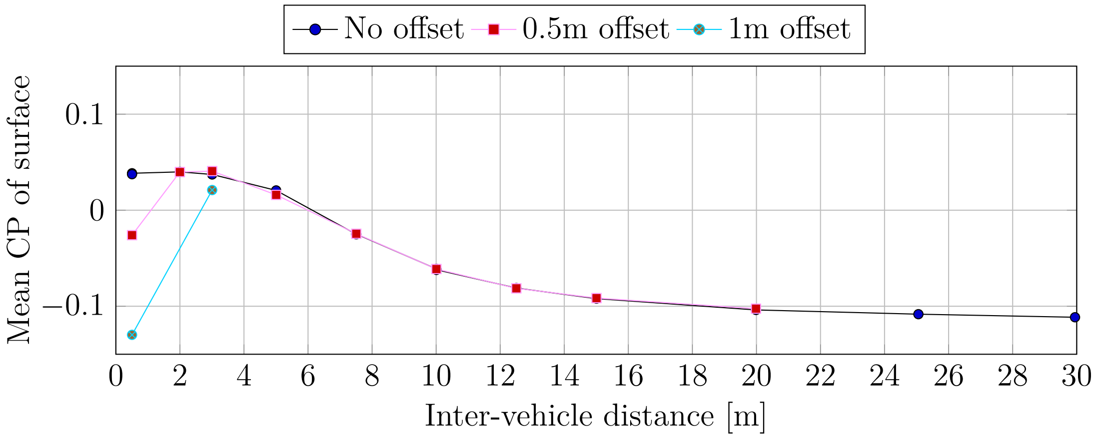
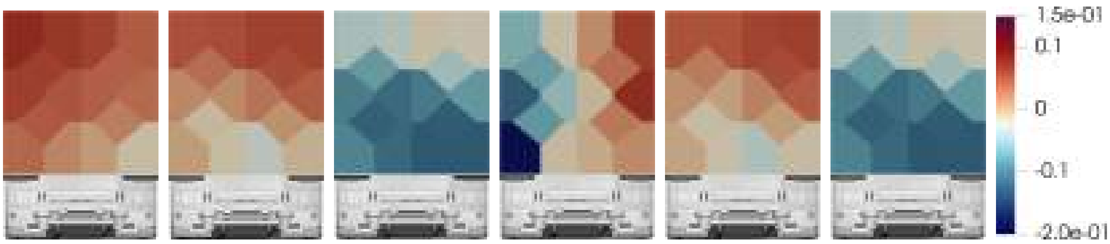


Figure 4.16: *Average base C_P for the leading truck versus inter-vehicle distance with and without lateral offset.*

Figure 4.17 presents the pressure on the base, which tends to become more uniform as the IVD decreases, even for the case with yaw, where large side-to-side asymmetries can be seen at longer IVDs. The figure also shows that the only case affected by a lateral offset is the shortest IVD. Similar changes to those of the zero yaw case can be seen where the leading truck interacts with the trailing truck forming something akin to a backward-facing step.



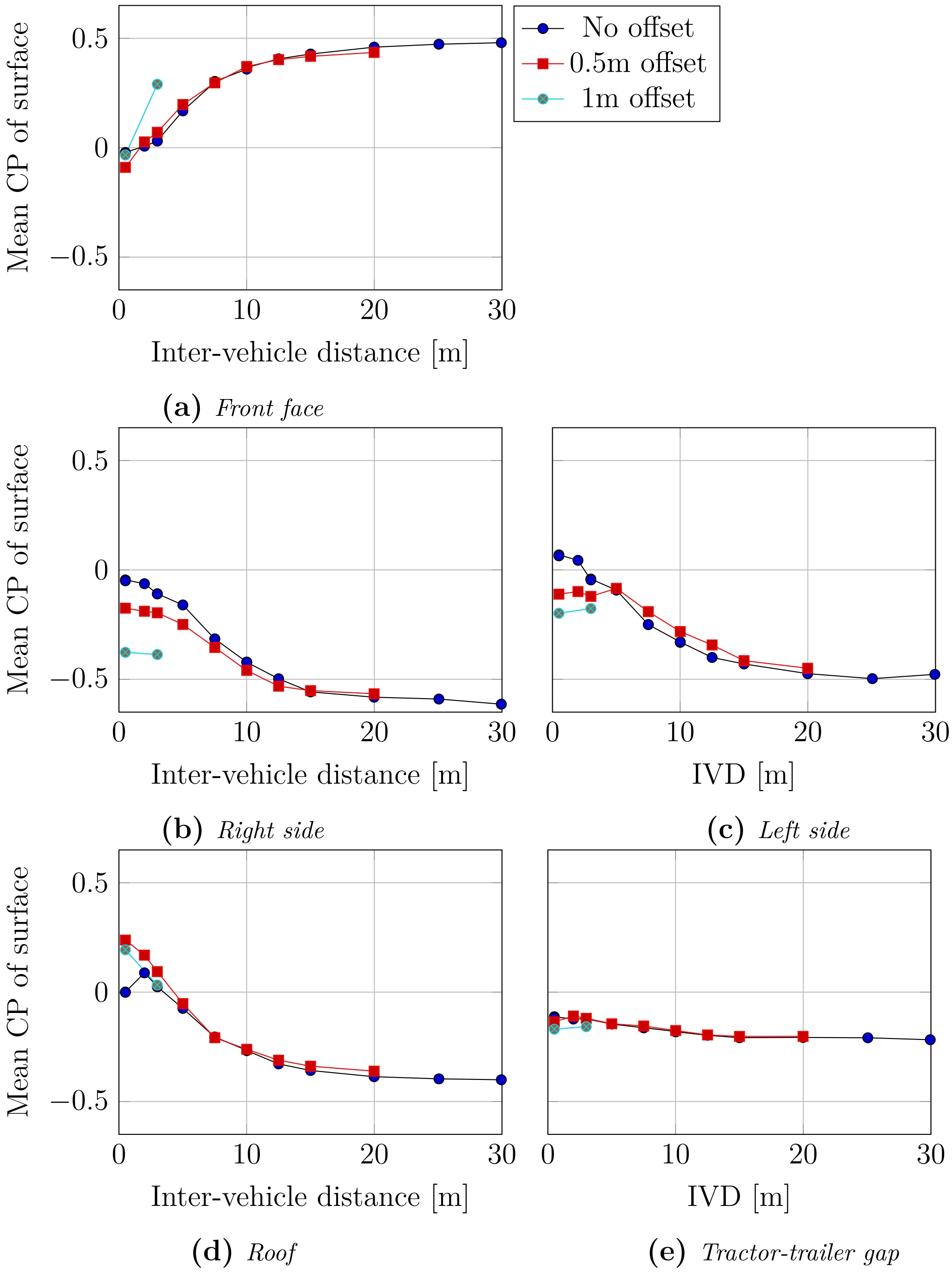
(a) *0.5m* **(b)** *5m* **(c)** *12.5m* **(d)** *0.5m* **(e)** *5m* **(f)** *12.5m*

Figure 4.17: *Base C_P of the leading truck, a-c is with 0m offset and d-f is with 0.5m offset at 5°yaw. The values denote IVD*

4.3.2 Trailing truck

The trailing truck also sees a reduction in platooning efficiency from yaw conditions, and its loss of performance is more substantial than that of the leading truck, which is confirmed by other studies, e.g., by Smith et al. [55]. This difference in performance is likely due to the different mechanisms at work for drag reduction, i.e., pressure changes for the leading truck and flow changes for the trailing truck. The changes can, in some circumstances, almost negate the effects of platooning completely, such as at 5m IVD and with no lateral offset. As discussed in other studies, there are ways of mitigating these negative effects from yaw conditions.

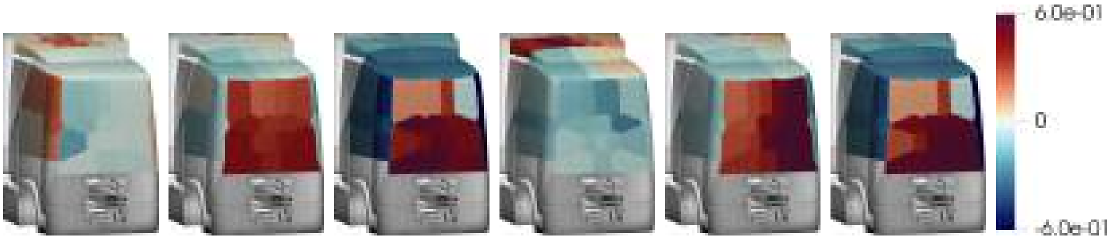
The one used here is applying a lateral offset in the leeward direction so as to move the trailing truck back into the wake of the leading truck. This has been shown to work well for IVDs greater than 1m and, in some cases, reduced the drag by up to 8%.



(a) *Front face* **(b)** *Right side* **(c)** *Left side* **(d)** *Roof* **(e)** *Tractor-trailer gap*

Figure 4.18: *Average C_P on the different surfaces on the front of the trailing truck versus IVD with and without lateral offset, 5°yaw.*

These improvements in drag are believed to originate from changes on the front edge radii, as they see a significant reduction of pressure with added offset, Figure 4.18. These changes are thought to stem from the leeward edge moving out of the wake of the leading truck into the freestream thus increasing the acceleration over the radii and thereby decreasing the pressure. For the windward side, the pressure is reduced as the oncoming flow angle changes when it moves into the wake and potentially decreases the amount of air that can cross from the windward to the leeward side, reducing the flow impingement that occurs at yaw. This lowering of pressure on the radii causes a decrease in drag as there is no significant change in the pressures elsewhere on the cab of the trailing vehicle.



(a) *0.5m* **(b)** *5m* **(c)** *12.5m* **(d)** *0.5m* **(e)** *5m* **(f)** *12.5m*

Figure 4.19: *Tractor C_P of the trailing truck, a-c is with 0m offset and d-f is with 0.5m offset at 5°yaw. The values denote IVD*

Figure 4.19 shows that there is always some asymmetry to the pressure at the trailing truck's front for the yaw case. It can further be seen that the added lateral offset does not cause symmetry of the pressure at the front face, which could be expected to yield the lowest drag. However, the average pressure at the front face does not change with the addition of a lateral offset, as shown in Figure 4.18a.

Chapter 5

Concluding remarks

This thesis has had several goals, the first being to develop a robust, affordable, and sufficiently accurate numerical method. The second goal was to create an experimental setup that allowed vehicles in close proximity to be investigated while using a moving ground system. The two methods gave similar trends and results and further agreed well with the results of several other studies available in the literature. The third goal was to investigate the aerodynamic behavior of two COE style tractor-trailer combinations in close proximity while varying IVD, lateral offset, and yaw. The results have shown that the leading truck has a fairly straightforward drag reduction mechanism in that it is mainly pressure-based and is determined mainly by the increase in pressure originating at the stagnation point of the trailing truck However, this is only the case at IVDs greater than roughly 5m. Below this distance, the space between the two trucks can be described as an open-sided cavity found in the tractor-trailer gap, for example. As for the trailing truck, the mechanisms are far more complex and produce both increases in drag as well as decreases. The main effects for the trailing truck are, according to when they are dominant, in terms of longest to shortest IVD:

- A reduced oncoming velocity yielding lower stagnation pressures and accelerations around the front edge roundings.
- Flow impingement on the front radii at short IVDs.
- Reduced efficiency of the roof air-deflector due to lower energy in the oncoming flow as well as changed flow angle on top of the vehicle, giving higher pressures in the tractor-trailer gap.

These three main effects balance each other and create the drag curve seen for the trailing truck in Figure 4.4b.

Another important observation is the behavior of a platoon under yaw conditions where the trailing truck sees a large reduction in performance and the leading truck sees a small reduction in performance. The main takeaway from this is that the trailing truck is mostly affected by changes in flow, whereas the leading truck is mainly affected by changes in pressure. With the yaw angles used in this study, the pressure field between the trucks is not sufficiently affected to cause large changes in drag for the leading truck. However, the trailing truck is affected significantly, especially at slightly longer IVDs where the change in wake direction shifts the point of interaction with the wake far enough to cause large increases in drag. The effects for the trailing truck were somewhat mitigated by the application of lateral offset and was shown to yield a drag reduction of up to 8%.

Chapter 6

Future work

The continuation of this work will mainly be focused on understanding the behavior of other types of vehicles in mixed platoons, such as an SUV and a bus. A wind tunnel test of an SUV and a truck has already been performed, with the SUV being used to measure forces on. Analysis of these results is ongoing. Further numerical simulations will be performed with both yaw conditions and lateral offset to further understand the behavior of vehicles in a platoon under these conditions. Simulations containing many more vehicles are also underway to understand the behavior when more than two trucks are involved. Flow measurements will also be done in the experimental setup to further validate the numerical simulations and better understand the behavior of the experimental method. Finally, attempts at improving the vehicle shape for better performance when driving in close proximity will be made. Some of the initial ideas are to increase the angle of the roof deflector at short IVDs to mitigate the drag increase seen from the tractor-trailer gap as well as the addition of boat tail extensions to the leading truck, as this has been shown to potentially increase the performance in a platoon.

Bibliography

[1] European Environment Agency. *Greenhouse gas emissions from transport*. 2019. URL: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12 (visited on 10/19/2020).

[2] Hannah Ritchie and Max Roser. *Emissions by sector*. URL: https://ourworldindata.org/emissions-by-sector (visited on 04/19/2021).

[3] Arturo Davila, Enric Aramburu, and Alex Freixas. "Making the Best Out of Aerodynamics: Platoons". In: *SAE 2013 World Congress & Exhibition*. SAE International, 2013. DOI: https://doi.org/10.4271/2013-01-0767. URL: https://doi.org/10.4271/2013-01-0767.

[4] Fred Browand, John Mcarthur, and Charles Radovich. "Fuel Saving Achieved in the Field Test of Two Tandem Trucks". In: *Institute of Transportation Studies, UC Berkeley, Institute of Transportation Studies, Research Reports, Working Papers, Proceedings* (Jan. 2004).

[5] Christophe Bonnet and Hans Fritz. "Fuel Consumption Reduction in a Platoon: Experimental Results with two Electronically Coupled Trucks at Close Spacing". In: *Future Transportation Technology Conference & Exposition*. SAE International, 2000. DOI: https://doi.org/10.4271/2000-01-3056. URL: https://doi.org/10.4271/2000-01-3056.

[6] Michael P. Lammert, Kenneth J. Kelly, and Janet Yanowitz. "Correlations of Platooning Track Test and Wind Tunnel Data". In: (Feb. 2018). DOI: 10.2172/1422885. URL: https://www.osti.gov/biblio/1422885.

[7] Assad Al Alam, Ather Gattami, and Karl Henrik Johansson. "An experimental study on the fuel reduction potential of heavy duty vehicle platooning". In: *13th International IEEE Conference on Intelligent Transportation Systems*. 2010, pp. 306–311. DOI: 10.1109/ITSC.2010.5625054.

[8] COOPER KR. "A WIND TUNNEL INVESTIGATION INTO THE FUEL SAVINGS AVAILABLE FROM THE AERODYNAMIC DRAG REDUCTION OF TRUCKS." English. In: *QUART. BULL. DIV. MECH. ENGNG NATION. AERONAUT. ESTABL.; CANADA; DA. 1976; NO 3; PP. 31-86* (1976).

[9] Kevin R. Cooper. "Wind Tunnel and Track Tests of Class 8 Tractors Pulling Single and Tandem Trailers Fitted with Side Skirts and Boat-tails". In: *SAE International Journal of Commercial Vehicles* 5.1 (2012), pp. 1–17. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2012-01-0104. URL: https://doi.org/10.4271/2012-01-0104.

[10] Jason Leuschen and Kevin R. Cooper. "Full-Scale Wind Tunnel Tests of Production and Prototype, Second-Generation Aerodynamic Drag-Reducing Devices for Tractor-Trailers". In: *SAE 2006 Commercial Vehicle Engineering Congress & Exhibition*. SAE International, 2006. DOI: https://doi.org/10.4271/2006-01-3456. URL: https://doi.org/10.4271/2006-01-3456.

[11] Kevin R. Cooper and Jason Leuschen. "Model and Full-Scale Wind Tunnel Tests of Second-Generation Aerodynamic Fuel Saving Devices for Tractor-Trailers". In: *2005 SAE Commercial Vehicle Engineering Conference*. SAE International, 2005. DOI: https://doi.org/10.4271/2005-01-3512. URL: https://doi.org/10.4271/2005-01-3512.

[12] Kevin R. Cooper. "Truck Aerodynamics Reborn - Lessons from the Past". In: *International Truck & Bus Meeting & Exhibition*. SAE International, 2003. DOI: https://doi.org/10.4271/2003-01-3376. URL: https://doi.org/10.4271/2003-01-3376.

[13] Kevin R. Cooper. "The Effect of Front-Edge Rounding and Rear-Edge Shaping on the Aerodynamic Drag of Bluff Vehicles in Ground Proximity". In: *SAE International Congress and Exposition*. SAE International, 1985. DOI: https://doi.org/10.4271/850288. URL: https://doi.org/10.4271/850288.

[14] Jason Leuschen. “Considerations for the Wind Tunnel Simulation of Tractor-Trailer Combinations: Correlation of Full- and Half-Scale Measurements”. In: *SAE International Journal of Commercial Vehicles* 6.2 (2013), pp. 529–538. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2013-01-2456. URL: https://doi.org/10.4271/2013-01-2456.

[15] Richard Wood. “Reynolds Number Impact on Commercial Vehicle Aerodynamics and Performance”. In: *SAE International Journal of Commercial Vehicles* 8.2 (2015), pp. 590–667. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2015-01-2859. URL: https://doi.org/10.4271/2015-01-2859.

[16] Jason Leuschen. “The Effects of Ground Simulation on Tractor-Trailer Combinations”. In: *SAE International Journal of Commercial Vehicles* 6.2 (2013), pp. 510–521. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2013-01-2454. URL: https://doi.org/10.4271/2013-01-2454.

[17] Jason Leuschen and Youssef Mébarki. “Examination of the Maskell III Blockage Correction Technique for Full Scale Testing in the NRC 9-Meter Wind Tunnel”. In: *SAE International Journal of Commercial Vehicles* 5.2 (2012), pp. 640–649. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2012-01-2047. URL: https://doi.org/10.4271/2012-01-2047.

[18] Helena Martini, Peter Gullberg, and Lennart Lofdahl. “Comparative Studies between CFD and Wind Tunnel Measurements of Cooling Performance and External Aerodynamics for a Heavy Truck”. In: *SAE International Journal of Commercial Vehicles* 7.2 (2014), pp. 640–652. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2014-01-2443. URL: https://doi.org/10.4271/2014-01-2443.

[19] Raja Sengupta, Jeremy Beedy, and Kevin Horrigan. “Combined Analysis of Cooling Airflow and Aerodynamic Drag for a Class 8 Tractor Trailer Combination”. In: *SAE International Journal of Commercial Vehicles* 4.1 (2011), pp. 263–274. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2011-01-2288. URL: https://doi.org/10.4271/2011-01-2288.

[20] Brian McAuliffe et al. “Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control”. In: *WCX World Congress Experience*. SAE International, 2018. DOI: https://doi.org/10.4271/2018-01-1181. URL: https://doi.org/10.4271/2018-01-1181.

[21] Rick Mihelic, Jeff Smith, and Matthew Ellis. “Aerodynamic Comparison of Tractor-Trailer Platooning and A-Train Configuration”. In: *SAE International Journal of Commercial Vehicles* 8.2 (2015), pp. 740–746. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2015-01-2897. URL: https://doi.org/10.4271/2015-01-2897.

[22] Kuo-Yun Liang, Jonas Mårtensson, and Karl H. Johansson. “Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data”. In: *2014 IEEE Intelligent Vehicles Symposium Proceedings*. 2014, pp. 1061–1068. DOI: 10.1109/IVS.2014.6856540.

[23] D. Bevly et al. “Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase One Final Report”. In: 2015.

[24] Sadayuki Tsugawa, Shin Kato, and Keiji Aoki. “An automated truck platoon for energy saving”. In: *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2011, pp. 4109–4114. DOI: 10.1109/IROS.2011.6094549.

[25] Arturo Dávila and Mario Nombela. “Sartre - Safe Road Trains for the Environment Reducing Fuel Consumption through Lower Aerodynamic Drag Coefficient”. In: *SAE Brasil 2011 Congress and Exhibit*. SAE International, 2011. DOI: https://doi.org/10.4271/2011-36-0060. URL: https://doi.org/10.4271/2011-36-0060.

[26] Michael P. Lammert et al. “Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass”. In: *SAE International Journal of Commercial Vehicles* 7.2 (2014), pp. 626–639. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2014-01-2438. URL: https://doi.org/10.4271/2014-01-2438.

[27] Michael P. Lammert et al. "Impact of Lateral Alignment on the Energy Savings of a Truck Platoon". In: *WCX SAE World Congress Experience*. SAE International, 2020. DOI: https://doi.org/10.4271/2020-01-0594. URL: https://doi.org/10.4271/2020-01-0594.

[28] Brian McAuliffe et al. "Impact of Mixed Traffic on the Energy Savings of a Truck Platoon". In: *SAE International Journal of Advances and Current Practices in Mobility* 2.3 (2020), pp. 1472–1496. ISSN: 2641-9637. DOI: https://doi.org/10.4271/2020-01-0679. URL: https://doi.org/10.4271/2020-01-0679.

[29] B. McAuliffe et al. "Fuel-economy testing of a three-vehicle truck platooning system". In: LTR-AL-2017-0008. Laboratory Technical Report (National Research Council of Canada. Aerospace. Aerodynamics Laboratory), Apr. 2017. DOI: https://doi.org/10.4224/23001922.

[30] Martin Passmore et al. "Increasing the on-road fuel economy by trailing at a safe distance." In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 231.9 (2017), pp. 1303 –1311. ISSN: 09544070. URL: https://search.ebscohost.com/login.aspx?direct=true&db=edo&AN=ejs42925230&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds.

[31] R. Veldhuizen, G.M.R. Van Raemdonck, and J.P. van der Krieke. "Fuel economy improvement by means of two European tractor semi-trailer combinations in a platooning formation". In: *Journal of Wind Engineering and Industrial Aerodynamics* 188 (2019), pp. 217–234. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.03.002. URL: https://www.sciencedirect.com/science/article/pii/S0167610518307700.

[32] Sadayuki Tsugawa. "Results and issues of an automated truck platoon within the energy ITS project". In: *2014 IEEE Intelligent Vehicles Symposium Proceedings*. 2014, pp. 642–647. DOI: 10.1109/IVS.2014.6856400.

[33] Patrick Hong et al. "Drag Forces Experienced by Two, Full-Scale Vehicles at Close Spacing". In: *International Congress & Exposition*. SAE International, 1998. DOI: https://doi.org/10.4271/980396. URL: https://doi.org/10.4271/980396.

[34] Paolo Schito and Francesco braghin. "Numerical and Experimental Investigation on Vehicles in Platoon". In: *SAE International Journal of Commercial Vehicles* 5.1 (2012), pp. 63–71. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2012-01-0175. URL: https://doi.org/10.4271/2012-01-0175.

[35] Debojyoti Mitra and Asis Mazumdar. "Pollution control by reduction of drag on cars and buses through platooning". In: *International Journal of Environment and Pollution - INT J ENVIRON POLLUTION* 30 (Jan. 2007). DOI: 10.1504/IJEP.2007.014504.

[36] Armagan Altinisik, Onur Yemenici, and Habib Umur. "Aerodynamic Analysis of a Passenger Car at Yaw Angle and Two-Vehicle Platoon". In: *Journal of Fluids Engineering* 137.12 (Aug. 2015). 121107. ISSN: 0098-2202. DOI: 10.1115/1.4030869. eprint: https://asmedigitalcollection.asme.org/fluidsengineering/article-pdf/137/12/121107/6195310/fe_137_12_121107.pdf. URL: https://doi.org/10.1115/1.4030869.

[37] Geoff Le Good et al. "Effects on the Aerodynamic Characteristics of Vehicles in Longitudinal Proximity Due to Changes in Style". In: *CO2 Reduction for Transportation Systems Conference*. SAE International, 2018. DOI: https://doi.org/10.4271/2018-37-0018. URL: https://doi.org/10.4271/2018-37-0018.

[38] Brian McAuliffe and Mojtaba Ahmadi-Baloutaki. "An Investigation of the Influence of Close-Proximity Traffic on the Aerodynamic Drag Experienced by Tractor-Trailer Combinations". In: *SAE International Journal of Advances and Current Practices in Mobility* 1.3 (2019), pp. 1251–1264. ISSN: 2641-9637. DOI: https://doi.org/10.4271/2019-01-0648. URL: https://doi.org/10.4271/2019-01-0648.

[39] Geoffrey Le Good et al. “An Investigation of Aerodynamic Characteristics of Three Bluff Bodies in Close Longitudinal Proximity”. In: *WCX SAE World Congress Experience*. SAE International, 2019. DOI: https://doi.org/10.4271/2019-01-0659. URL: https://doi.org/10.4271/2019-01-0659.

[40] Simon Watkins and Gioacchino Vino. “The effect of vehicle spacing on the aerodynamics of a representative car shape”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 96.6 (2008). 5th International Colloquium on Bluff Body Aerodynamics and Applications, pp. 1232–1239. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2007.06.042. URL: https://www.sciencedirect.com/science/article/pii/S0167610507001687.

[41] C.A.J. Fletcher and G.D.H. Stewart. “Bus drag reduction by the trapped vortex concept for a single bus and two buses in tandem”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 24.2 (1986), pp. 143–168. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(86)90004-8. URL: https://www.sciencedirect.com/science/article/pii/0167610586900048.

[42] M. Hammache, M. Michaelian, and F. Browand. “Aerodynamic Forces on Truck Models, Including Two Trucks in Tandem”. In: *SAE 2002 World Congress & Exhibition*. SAE International, 2002. DOI: https://doi.org/10.4271/2002-01-0530. URL: https://doi.org/10.4271/2002-01-0530.

[43] Kambiz Salari and Jason Ortega. “Experimental Investigation of the Aerodynamic Benefits of Truck Platooning”. In: *WCX World Congress Experience*. SAE International, 2018. DOI: https://doi.org/10.4271/2018-01-0732. URL: https://doi.org/10.4271/2018-01-0732.

[44] Paolo Schito and Francesco braghin. “Numerical and Experimental Investigation on Vehicles in Platoon”. In: *SAE International Journal of Commercial Vehicles* 5.1 (2012), pp. 63–71. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2012-01-0175. URL: https://doi.org/10.4271/2012-01-0175.

[45] Lun Tsuei and Ömer Savaş. “Transient aerodynamics of vehicle platoons during in-line oscillations”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 89.13 (2001), pp. 1085–1111. ISSN: 0167-6105. DOI: https://doi.org/10.1016/S0167-6105(01)00073-3. URL: https://www.sciencedirect.com/science/article/pii/S0167610501000733.

[46] J.F. Huang, T.L. Chan, and Y. Zhou. “Three-dimensional flow structure measurements behind a queue of studied model vehicles”. In: *International Journal of Heat and Fluid Flow* 30.4 (2009), pp. 647–657. ISSN: 0142-727X. DOI: https://doi.org/10.1016/j.ijheatfluidflow.2009.03.010. URL: https://www.sciencedirect.com/science/article/pii/S0142727X09000666.

[47] Brian R. McAuliffe and Mojtaba Ahmadi-Baloutaki. “A Wind-Tunnel Investigation of the Influence of Separation Distance, Lateral Stagger, and Trailer Configuration on the Drag-Reduction Potential of a Two-Truck Platoon”. In: *SAE International Journal of Commercial Vehicles* 11.2 (2018), pp. 125–150. ISSN: 1946-391X. DOI: https://doi.org/10.4271/02-11-02-0011. URL: https://doi.org/10.4271/02-11-02-0011.

[48] Michael Zabat, Stefano Frascaroli, and F. K. Browand. “Drag Measurements on 2, 3 and 4 Car Platoons”. In: *International Congress & Exposition*. SAE International, 1994. DOI: https://doi.org/10.4271/940421. URL: https://doi.org/10.4271/940421.

[49] Kambiz Salari and Jason Ortega. “Experimental Investigation of the Aerodynamic Benefits of Truck Platooning”. In: *WCX World Congress Experience*. SAE International, 2018. DOI: https://doi.org/10.4271/2018-01-0732. URL: https://doi.org/10.4271/2018-01-0732.

[50] D.P. Telionis, C.J. Fahrner, and G.S. Jones. “An experimental study of highway aerodynamic interferences.” In: *Journal of Wind Engineering & Industrial Aerodynamics* 17.3 (1984), pp. 267 –293. ISSN: 0167-6105. URL: https://search.ebscohost.com/login.aspx?direct=true&db=edselp&AN=0167610584900217&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds.

[51] Bogdan Marcu and Fred Browand. “Aerodynamic Forces Experienced by a 3-Vehicle Platoon in a Crosswind”. In: *International Congress & Exposition*. SAE International, 1999. DOI: https://doi.org/10.4271/1999-01-1324. URL: https://doi.org/10.4271/1999-01-1324.

[52] Francis H. Robertson et al. “An experimental investigation of the aerodynamic flows created by lorries travelling in a long platoon”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 193 (2019), p. 103966. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.103966. URL: https://www.sciencedirect.com/science/article/pii/S0167610519305641.

[53] Kenji Tadakuma et al. “Prediction formula of Aerodynamic Drag Reduction in Multiple-Vehicle Platooning Based on Wake Analysis and On-Road Experiments”. In: *SAE International Journal of Passenger Cars - Mechanical Systems* 9.2 (2016), pp. 645–656. ISSN: 1946-3995. DOI: https://doi.org/10.4271/2016-01-1596. URL: https://doi.org/10.4271/2016-01-1596.

[54] Hugh Humphreys and David Bevly. “Computational Fluid Dynamic Analysis of a Generic 2 Truck Platoon”. In: *SAE 2016 Commercial Vehicle Engineering Congress*. SAE International, 2016. DOI: https://doi.org/10.4271/2016-01-8008. URL: https://doi.org/10.4271/2016-01-8008.

[55] Jeff Smith et al. “Aerodynamic Impact of Tractor-Trailer in Drafting Configuration”. In: *SAE International Journal of Commercial Vehicles* 7.2 (2014), pp. 619–625. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2014-01-2436. URL: https://doi.org/10.4271/2014-01-2436.

[56] Prasad Vegendla et al. “Investigation of Aerodynamic Influence on Truck Platooning”. In: *SAE 2015 Commercial Vehicle Engineering Congress*. SAE International, 2015. DOI: https://doi.org/10.4271/2015-01-2895. URL: https://doi.org/10.4271/2015-01-2895.

[57] Hugh Luke Humphreys et al. “An Evaluation of the Fuel Economy Benefits of a Driver Assistive Truck Platooning Prototype Using Simulation”. In: *SAE 2016 World Congress and Exhibition*. SAE International, 2016. DOI: https://doi.org/10.4271/2016-01-0167. URL: https://doi.org/10.4271/2016-01-0167.

[58] Hugh Luke Humphreys et al. “An Evaluation of the Fuel Economy Benefits of a Driver Assistive Truck Platooning Prototype Using Simulation”. In: *SAE 2016 World Congress and Exhibition*. SAE International, 2016. DOI: https://doi.org/10.4271/2016-01-0167. URL: https://doi.org/10.4271/2016-01-0167.

[59] Rikard Laxhammar and Albert Gascón-Vallbona. “COMPANION D4.3. Vehicle models for fuel consumption”. In: *European Commission* Ref. Ares(2015)4007967 (2015).

[60] Mingzhe He et al. “Detached eddy simulation of a closely running lorry platoon”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 193 (2019), p. 103956. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.103956. URL: https://www.sciencedirect.com/science/article/pii/S0167610519305471.

[61] Charles-Henri Bruneau, Khodor Khadra, and Iraj Mortazavi. “Flow analysis of square-back simplified vehicles in platoon”. In: *International Journal of Heat and Fluid Flow* 66 (2017), pp. 43–59. ISSN: 0142-727X. DOI: https://doi.org/10.1016/j.ijheatfluidflow.2017.05.008. URL: https://www.sciencedirect.com/science/article/pii/S0142727X16306270.

[62] Hesham Ebrahim and Robert Dominy. “Wake and surface pressure analysis of vehicles in platoon”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 201 (2020), p. 104144. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2020.104144. URL: https://www.sciencedirect.com/science/article/pii/S0167610520300544.

[63] Matthew Ellis, Joaquin Ivan Gargoloff, and Raja Sengupta. “Aerodynamic Drag and Engine Cooling Effects on Class 8 Trucks in Platooning Configurations”. In: *SAE International Journal of Commercial Vehicles* 8.2 (2015), pp. 732–739. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2015-01-2896. URL: https://doi.org/10.4271/2015-01-2896.

[64] Thomas Gheyssens and Gandert Van Raemdonck. “Effect of the Frontal Edge Radius in a Platoon of Bluff Bodies”. In: *SAE International Journal of Commercial Vehicles* 9.2 (2016), pp. 371–380. ISSN: 1946-391X. DOI: https://doi.org/10.4271/2016-01-8149. URL: https://doi.org/10.4271/2016-01-8149.

[65] Surya Narayana Prasa Vegendla et al. "Investigation on Underhood Thermal Analysis of Truck Platooning". In: *SAE International Journal of Commercial Vehicles* 11.1 (2018), pp. 5–16. ISSN: 1946-391X. DOI: https://doi.org/10.4271/02-11-01-0001. URL: https://doi.org/10.4271/02-11-01-0001.

[66] Brian Block et al. "Analysis of the Effect of Vehicle Platooning on the Optimal Control of a Heavy Duty Engine Thermal System". In: *SAE International Journal of Advances and Current Practices in Mobility* 1.4 (2019), pp. 1661–1671. ISSN: 2641-9637. DOI: https://doi.org/10.4271/2019-01-1259. URL: https://doi.org/10.4271/2019-01-1259.

[67] Hesham Ebrahim, Robert Dominy, and Ken Leung. "Evaluation of vehicle platooning aerodynamics using bluff body wake generators and CFD." In: (2017). ISSN: 1-4673-9028-3. URL: https://search.ebscohost.com/login.aspx?direct=true&db=edsair&AN=edsair.core.ac.uk...0033a41f22ed649e22b41fe7e1d62ca0&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds.

[68] David Uystepruyst and Siniša Krajnović. "LES of the flow around several cuboids in a row". In: *International Journal of Heat and Fluid Flow* 44 (2013), pp. 414–424. ISSN: 0142-727X. DOI: https://doi.org/10.1016/j.ijheatfluidflow.2013.07.011. URL: https://www.sciencedirect.com/science/article/pii/S0142727X13001537.

[69] S.J. Price and M.P. Paidoussis. "The aerodynamic forces acting on groups of two and three circular cylinders when subject to a cross-flow". In: *Journal of Wind Engineering and Industrial Aerodynamics* 17.3 (1984), pp. 329–347. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(84)90024-2. URL: https://www.sciencedirect.com/science/article/pii/0167610584900242.

[70] M.M. Zdravkovich and D.L. Pridden. "Interference between two circular cylinders; Series of unexpected discontinuities". In: *Journal of Wind Engineering and Industrial Aerodynamics* 2.3 (1977), pp. 255–270. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(77)90026-5. URL: https://www.sciencedirect.com/science/article/pii/0167610577900265.

[71] D.P. Telionis, C.J. Fahrner, and G.S. Jones. "An experimental study of highway aerodynamic interferences." In: *Journal of Wind Engineering & Industrial Aerodynamics* 17.3 (1984), pp. 267 –293. ISSN: 0167-6105. URL: https://search.ebscohost.com/login.aspx?direct=true&db=edselp&AN=0167610584900217&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds.

[72] Eric Jacuzzi and Kenneth Granlund. "Passive flow control for drag reduction in vehicle platoons". In: *Journal of Wind Engineering and Industrial Aerodynamics* 189 (2019), pp. 104–117. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.03.001. URL: https://www.sciencedirect.com/science/article/pii/S0167610518309474.

[73] Bert Blocken et al. "Aerodynamic drag in cycling team time trials". In: *Journal of Wind Engineering and Industrial Aerodynamics* 182 (2018), pp. 128–145. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2018.09.015. URL: https://www.sciencedirect.com/science/article/pii/S0167610518306755.

[74] Bert Blocken et al. "Aerodynamic drag in cycling pelotons: New insights by CFD simulation and wind tunnel testing". In: *Journal of Wind Engineering and Industrial Aerodynamics* 179 (2018), pp. 319–337. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2018.06.011. URL: https://www.sciencedirect.com/science/article/pii/S0167610518303751.

[75] Chao Li et al. "Flow topology of a container train wagon subjected to varying local loading configurations". In: *Journal of Wind Engineering and Industrial Aerodynamics* 169 (2017), pp. 12–29. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2017.06.011. URL: https://www.sciencedirect.com/science/article/pii/S0167610516303385.

[76] Dominic Flynn, Hassan Hemida, and Chris Baker. "On the effect of crosswinds on the slipstream of a freight train and associated effects". In: *Journal of Wind Engineering and Industrial Aerodynamics* 156 (2016), pp. 14–28. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2016.07.001. URL: https://www.sciencedirect.com/science/article/pii/S0167610515300337.

[77] David Soper, Chris Baker, and Mark Sterling. “Experimental investigation of the slipstream development around a container freight train using a moving model facility”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 135 (2014), pp. 105–117. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2014.10.001. URL: https://www.sciencedirect.com/science/article/pii/S0167610514001949.

[78] Siavash Maleki, David Burton, and Mark C. Thompson. “Flow structure between freight train containers with implications for aerodynamic drag”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 188 (2019), pp. 194–206. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.02.007. URL: https://www.sciencedirect.com/science/article/pii/S0167610518309413.

[79] Siavash Maleki, David Burton, and Mark C. Thompson. “Assessment of various turbulence models (ELES, SAS, URANS and RANS) for predicting the aerodynamics of freight train container wagons”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 170 (2017), pp. 68–80. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2017.07.008. URL: https://www.sciencedirect.com/science/article/pii/S0167610517302921.

[80] J.W. Allan. “Aerodynamic drag and pressure measurements on a simplified tractor-trailer model”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 9.1 (1981), pp. 125–136. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(81)90083-0. URL: https://www.sciencedirect.com/science/article/pii/0167610581900830.

[81] Jan Östh and Siniša Krajnović. “The flow around a simplified tractor-trailer model studied by large eddy simulation”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 102 (2012), pp. 36–47. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2011.12.007. URL: https://www.sciencedirect.com/science/article/pii/S0167610511002522.

[82] Kevin P. Garry. “Some effects of ground clearance and ground plane boundary layer thickness on the mean base pressure of a bluff vehicle type body”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 62.1 (1996), pp. 1–10. ISSN: 0167-6105. DOI: https://doi.org/10.1016/S0167-6105(96)00054-2. URL: https://www.sciencedirect.com/science/article/pii/S0167610596000542.

[83] T. Avadiar et al. “The influence of reduced Reynolds number on the wake of the DrivAer estate vehicle”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 188 (2019), pp. 207–216. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.02.024. URL: https://www.sciencedirect.com/science/article/pii/S0167610518308596.

[84] T. Lajos, L. Preszler, and L. Finta. “Effect of moving ground simulation on the flow past bus models”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 22.2 (1986). Special Issue 6th Colloquium on Industrial Aerodynamics Vehicle Aerodynamics, pp. 271–277. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(86)90090-5. URL: https://www.sciencedirect.com/science/article/pii/0167610586900905.

[85] M. Sardou. ““Reynolds effect” and “moving ground effect” tested in a quarter scale wind tunnel over a high speed moving belt”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 22.2 (1986). Special Issue 6th Colloquium on Industrial Aerodynamics Vehicle Aerodynamics, pp. 245–270. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(86)90089-9. URL: https://www.sciencedirect.com/science/article/pii/0167610586900899.

[86] J. E. Hackett et al. “On the Influence of Ground Movement and Wheel Rotation in Tests on Modern Car Shapes”. In: *SAE International Congress and Exposition*. SAE International, 1987. DOI: https://doi.org/10.4271/870245. URL: https://doi.org/10.4271/870245.

[87] J.P Howell and K.W Everitt. “The underbody flow of an EDS-type advanced ground transport vehicle”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 8.3 (1981), pp. 275–294. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(81)90026-X. URL: https://www.sciencedirect.com/science/article/pii/016761058190026X.

[88] M.S. Kim and D. Geropp. “Experimental investigation of the ground effect on the flow around some two-dimensional bluff bodies with moving-belt technique”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 74-76 (1998), pp. 511–519. ISSN: 0167-6105. DOI: https://doi.org/10.1016/S0167-6105(98)00046-4. URL: https://www.sciencedirect.com/science/article/pii/S0167610598000464.

[89] Shibo Wang et al. “Effect of moving ground on the aerodynamics of a generic automotive model: The DrivAer-Estate”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 195 (2019), p. 104000. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.104000. URL: https://www.sciencedirect.com/science/article/pii/S0167610519306002.

[90] B. Fago, H. Lindner, and O. Mahrenholtz. “The effect of ground simulation on the flow around vehicles in wind tunnel testing”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 38.1 (1991), pp. 47–57. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(91)90026-S. URL: https://www.sciencedirect.com/science/article/pii/016761059190026S.

[91] K. Burgin, P.C. Adey, and J.P. Beatham. “Wind tunnel tests on road vehicle models using a moving belt simulation of ground effect”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 22.2 (1986). Special Issue 6th Colloquium on Industrial Aerodynamics Vehicle Aerodynamics, pp. 227–236. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(86)90087-5. URL: https://www.sciencedirect.com/science/article/pii/0167610586900875.

[92] C.J. Baker and N.J. Brockie. “Wind tunnel tests to obtain train aerodynamic drag coefficients: Reynolds number and ground simulation effects”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 38.1 (1991), pp. 23–28. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(91)90024-Q. URL: https://www.sciencedirect.com/science/article/pii/016761059190024Q.

[93] Emil Ljungskog, Simone Sebben, and Alexander Broniewicz. “Inclusion of the physical wind tunnel in vehicle CFD simulations for improved prediction quality”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 197 (2020), p. 104055. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2019.104055. URL: https://www.sciencedirect.com/science/article/pii/S0167610519306555.

[94] Petter Ekman et al. “Accuracy and Speed for Scale-Resolving Simulations of the DrivAer Reference Model”. In: *WCX SAE World Congress Experience*. SAE International, 2019. DOI: https://doi.org/10.4271/2019-01-0639. URL: https://doi.org/10.4271/2019-01-0639.

[95] Stephen B Pope. “Ten questions concerning the large-eddy simulation of turbulent flows”. In: *New Journal of Physics* 6 (2004), pp. 35–35. DOI: 10.1088/1367-2630/6/1/035. URL: https://doi.org/10.1088/1367-2630/6/1/035.

[96] E. Ljungskog, Chalmers tekniska högskola. Division of Division of Vehicle Engineering, and Autonomous Systems. *Evaluation and Modeling of the Flow in a Slotted Wall Wind Tunnel*. Doktorsavhandlingar vid Chalmers tekniska högskola. Department of Mechanics, Maritime Sciences, Division of Vehicle Engineering, and Autonomous Systems, Chalmers University of Technology, 2019. ISBN: 9789179052195. URL: https://books.google.se/books?id=adx0zQEACAAJ.

[97] Magnus Urquhart, Simone Sebben, and Lennert Sterken. “Numerical analysis of a vehicle wake with tapered rear extensions under yaw conditions”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 179 (2018), pp. 308–318. ISSN: 0167-6105. DOI: https://doi.org/10.1016/j.jweia.2018.06.001. URL: https://www.sciencedirect.com/science/article/pii/S0167610518301144.

[98] Lars Davidson. “Large Eddy Simulations: How to evaluate resolution”. In: *International Journal of Heat and Fluid Flow* 30.5 (2009). The 3rd International Conference on Heat Transfer and Fluid Flow in Microscale, pp. 1016–1025. ISSN: 0142-727X. DOI: https://doi.org/10.1016/j.ijheatfluidflow.2009.06.006. URL: https://www.sciencedirect.com/science/article/pii/S0142727X09001039.

[99] J1252. *SAE Wind Tunnel Test Procedure for Trucks and Buses*. SAE International Surface Vehicle Recommended Practice, SAE Standard J1252. Rev. August 2012. DOI: https://doi.org/10.4271/J1252_201207. URL: https://doi.org/10.4271/J1252_201207.

[100] Johan Sternéus, Tim Walker, and Trevor Bender. "Upgrade of the Volvo Cars Aerodynamic Wind Tunnel". In: *SAE World Congress & Exhibition*. SAE International, 2007. DOI: https://doi.org/10.4271/2007-01-1043. URL: https://doi.org/10.4271/2007-01-1043.